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GEOPHYSICS

A Journal of General and Applied Geophysics

Published Quarterly by the
Society of Exploration Geophysicists

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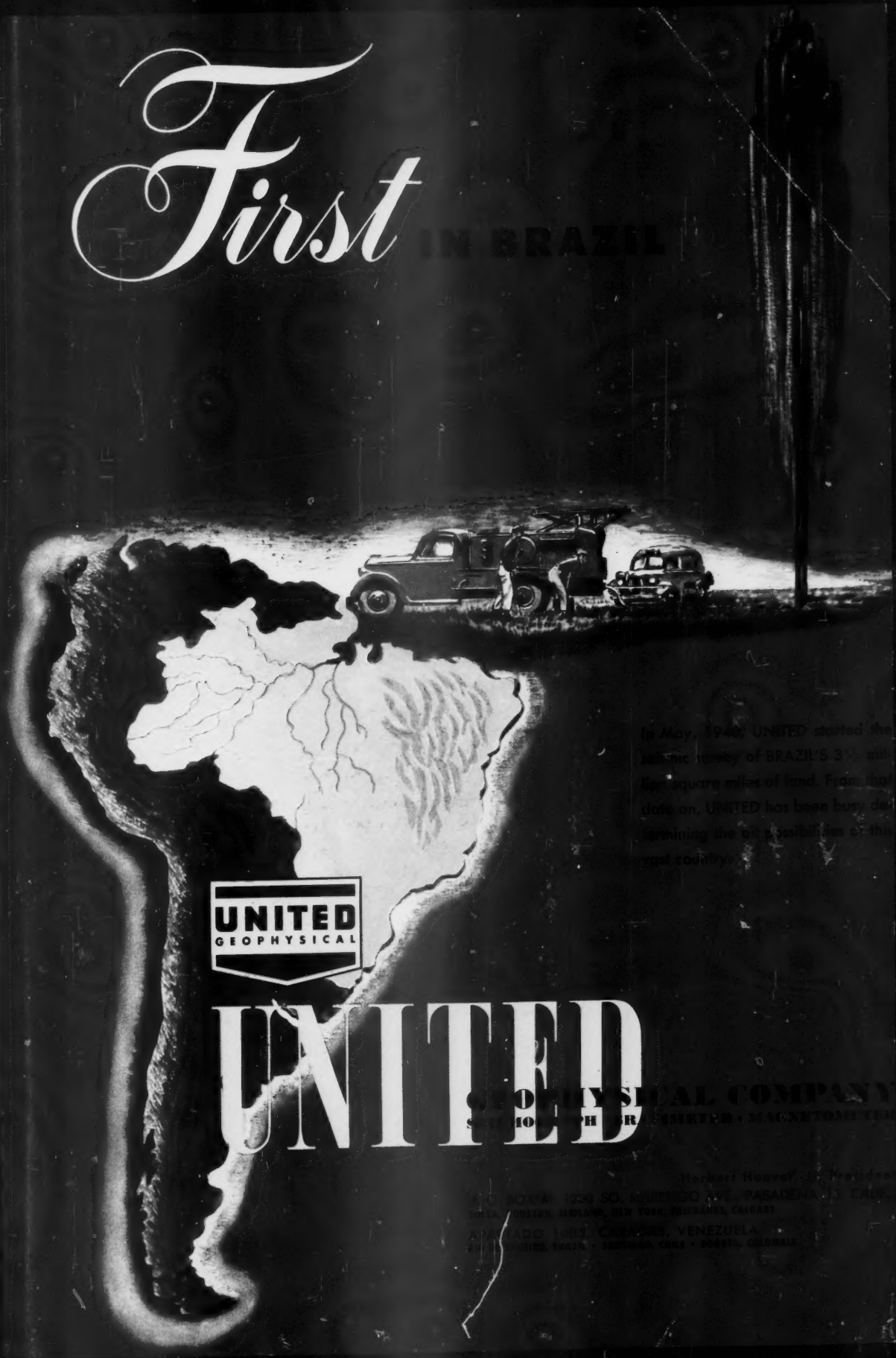

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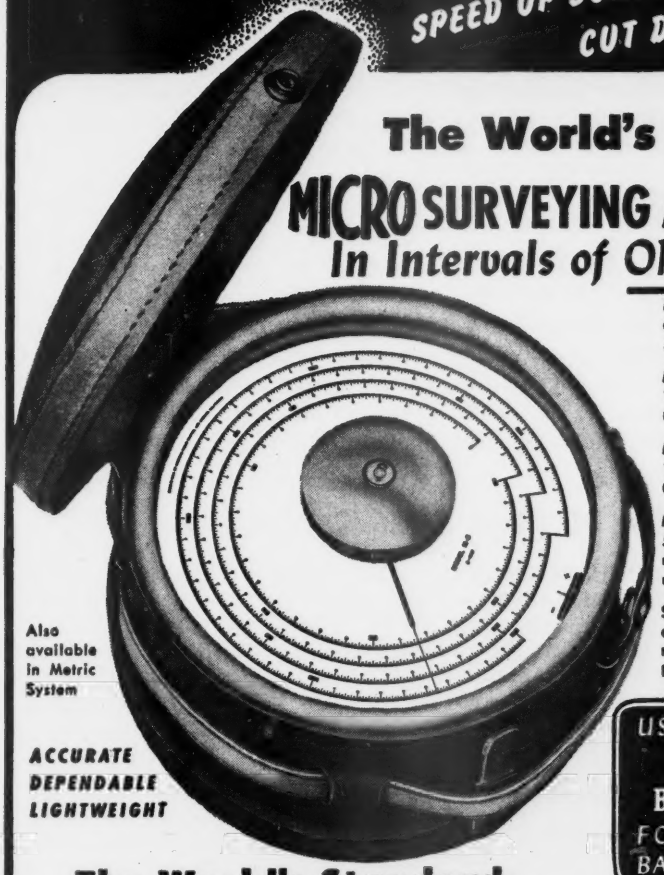

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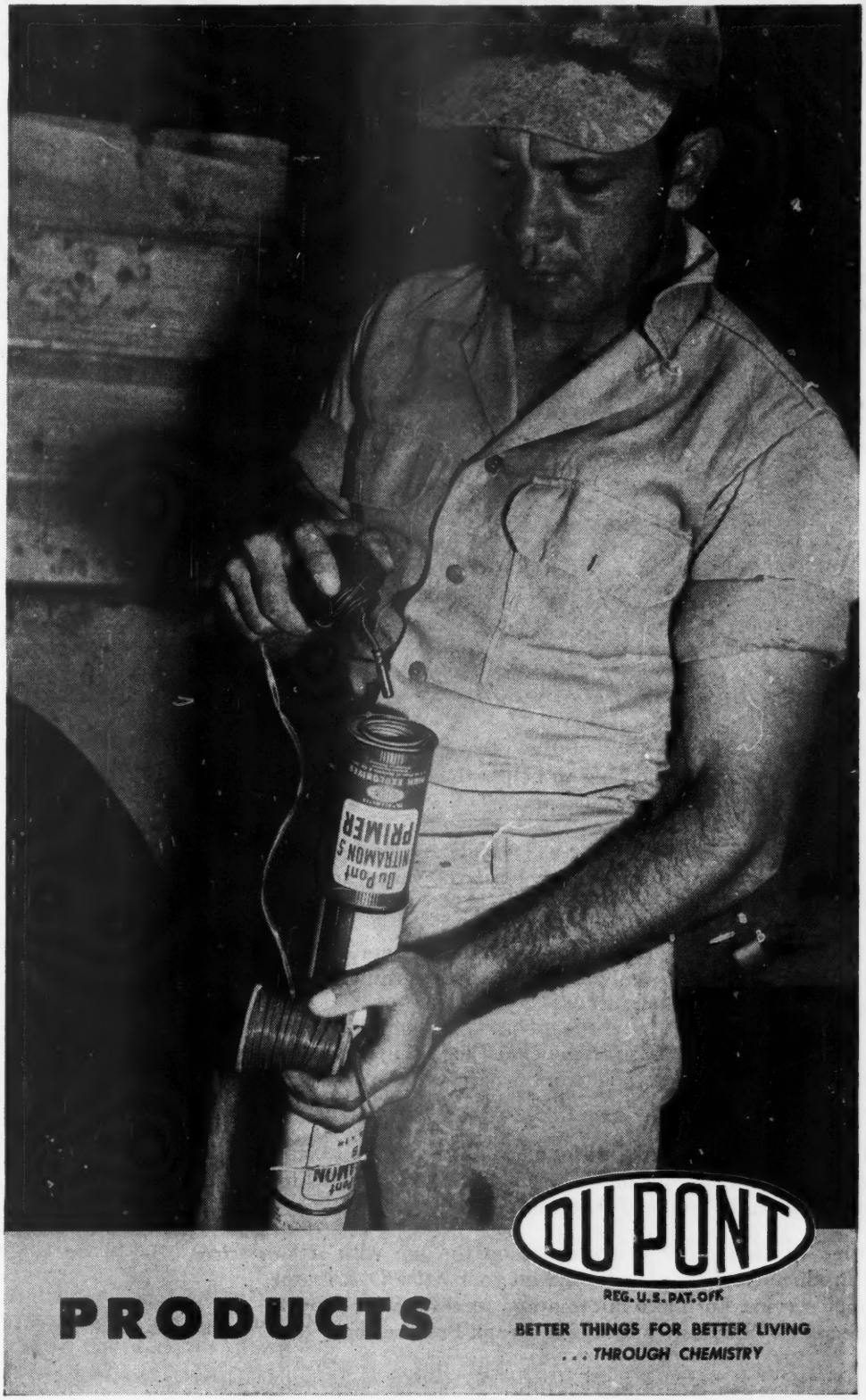
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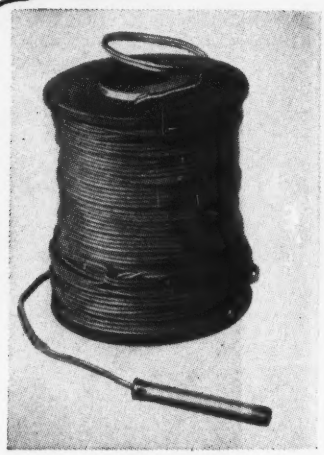

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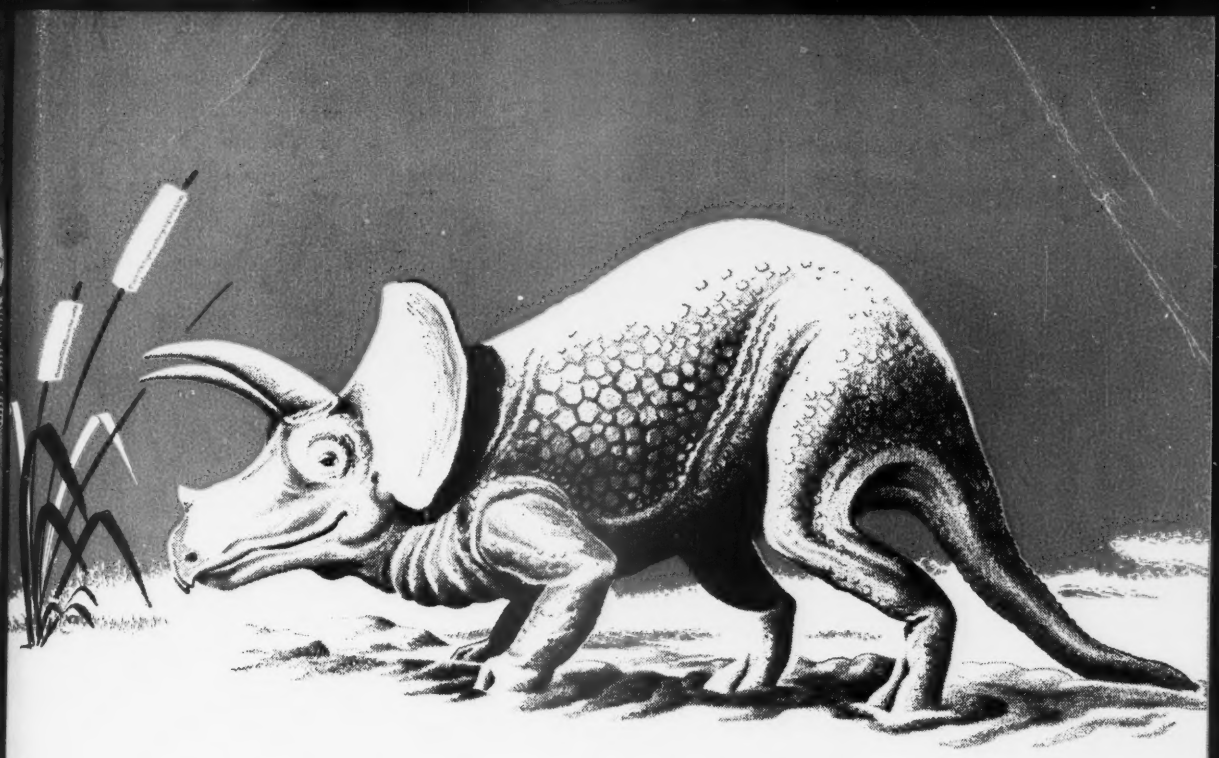

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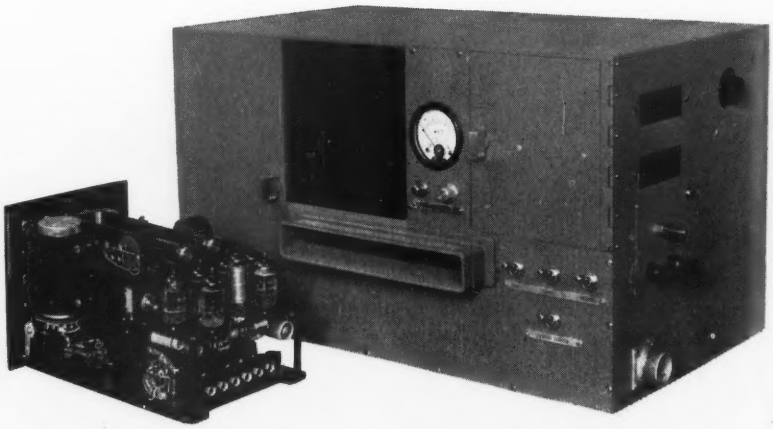

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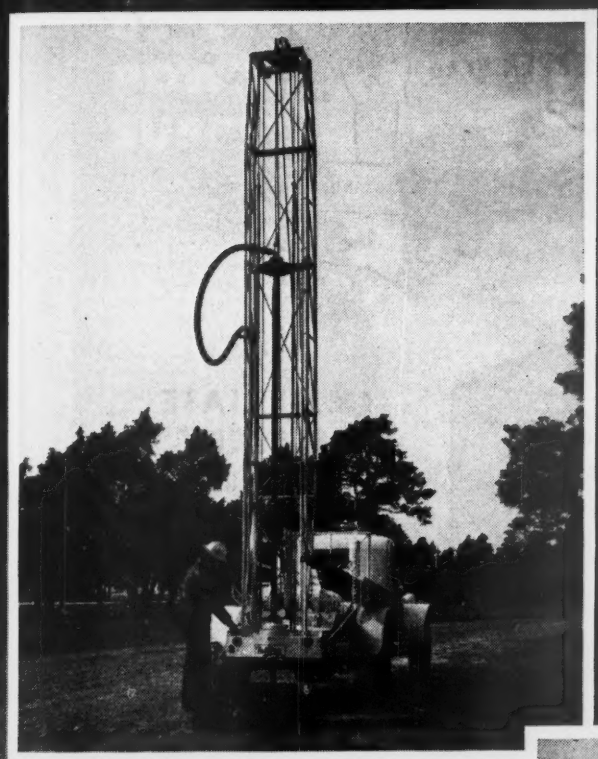

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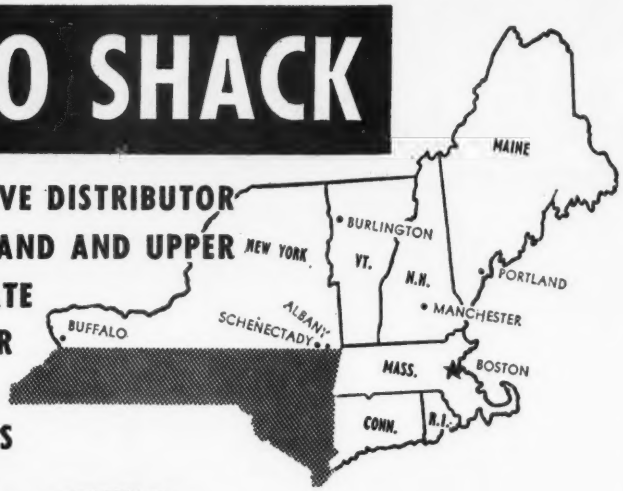

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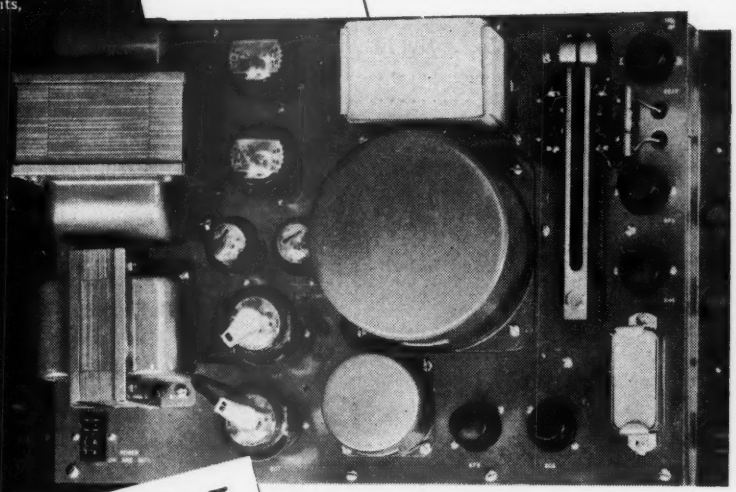

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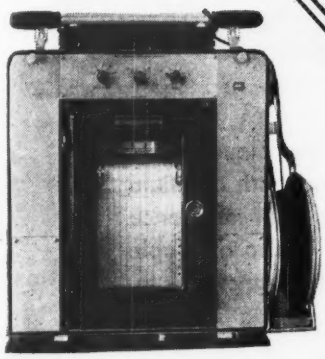

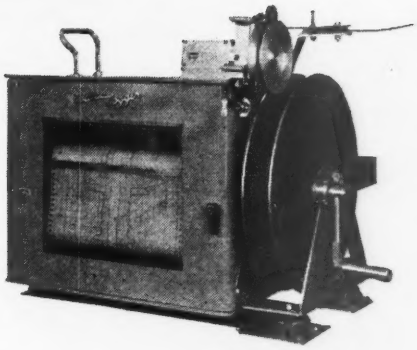

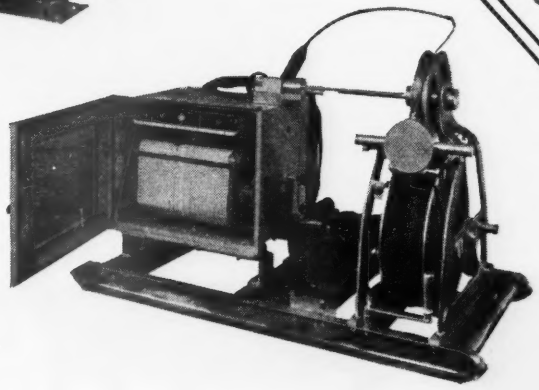

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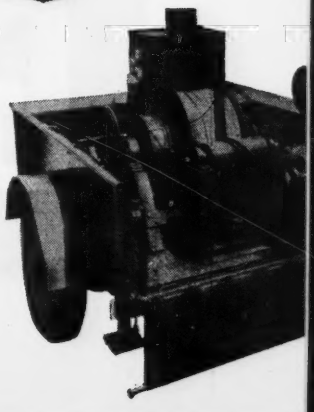

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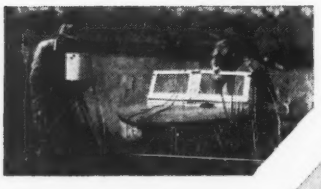

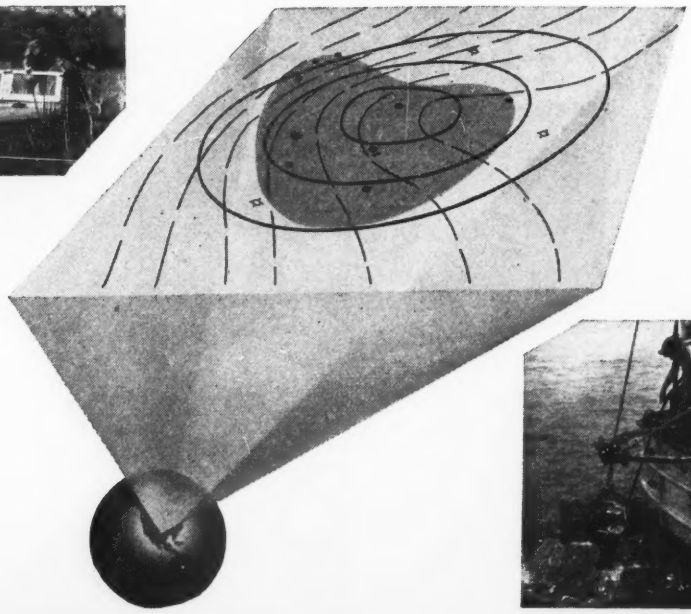

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VOLUME XVIII JANUARY, 1953 NUMBER 1

GEOPHYSICS

A Journal of General and Applied Geophysics

ADEQUATE GEOPHYSICAL MANPOWER IS OUR RESPONSIBILITY*

CURTIS H. JOHNSON†

Once again I am privileged to attend a Midcontinent Regional Meeting of the Society of Exploration Geophysicists—this time with the honor and responsibility of addressing you on a subject receiving increasingly serious consideration among scientific and engineering groups. As in the past I am highly impressed with the outstanding quality of the program and arrangements for this meeting. On behalf of the other officers of the national Society, who are all attending this meeting, I welcome this opportunity to congratulate the officers and committeemen of the sponsoring and participating societies for the successful culmination of their efforts and to commend the authors for their cooperation in contributing to this outstanding program.

The title of my talk today—"What is a Geophysicist?"*—is somewhat of an unfair teaser. I don't expect to tell you anything in reply to this question you don't already know. One of the things I do propose, however, is for us all to answer this question for the public at large which, when it gives the matter any thought at all, asks this question out of a profound ignorance of the answer. I'll always remember a personal experience in St. Louis at the time of the 1950 Annual Meeting of the Society. I was waiting at the cigar stand to buy a pack of cigarettes and overheard the customer ahead of me ask the girl at the counter who the people crowding the lobby were. I'll never forget her reply: "Oh, I believe part of them are the Society of Economic Geopsychics. I think they have something to do with reading the bumps on your head."

Perhaps some of you just laugh good-naturedly when such things happen to

* Presented as an S.E.G. Presidential Address at the Midwestern Regional Meeting in Fort Worth, Nov. 13, 1952 under the title "What is a Geophysicist?"

Essentially this same paper was presented as an S.E.G. Presidential address at the Eastern Region Meeting in Toronto, Oct. 27, 1952 and at the Pacific Coast Regional Meeting in Los Angeles, Oct. 31, 1952 under the title "Professional Responsibility."

† General Petroleum Corporation, Los Angeles, California.

you. Perhaps you have not been too concerned that the public knows little of our profession. Please bear with me while I outline reasons why we should be concerned with such misconceptions and suggest means for dispelling them.

This meeting, other local and regional meetings of the Society and the new Local Sections and Student Sections just formed and about to be formed are evidence of the growth in the amount and diversification of geophysical activity. Perhaps the most direct evidence of the increased use of geophysics as an exploration tool is given in the annual report of the S.E.G. Committee on Geophysical Activity presented at the last Annual Meeting by Dr. E. A. Eckhardt, chairman of the Committee, and published in the July, 1952 issue of *Geophysics*. In this report Dr. Eckhardt states that in 1951 there was a 20.4 percent increase in the seismograph work and 12.2 percent increase in the gravity work done for the oil industry as compared to 1950.

That this expansion is continuing is indicated by a recent report in the October 10, 1952 issue of *The Week in Review*, published by the Western Oil and Gas Association which states that 183 crews were operating in Canada in August 1952—a new all-time high. Since Mr. L. I. Brockway, President of the Canadian Society of Exploration Geophysicists has verified my suspicion that these are seismograph crews, these 183 crews represent an increase of 41 percent over the average for 1951. Even after applying a seasonal correction, this should represent a substantial increase in 1952 over 1951.

That there is also increased diversification in the use of geophysical exploration is indicated by Dr. Eckhardt's report that expenditures in geophysical exploration in the mining industry increased 50 percent in 1951 over 1950. Increased interest in mining geophysics is also shown by the attendance at the mining symposium at the annual meeting of the S.E.G. in Los Angeles in March, 1952 and by the splendid well-attended meeting in Toronto in October, 1952 which was devoted almost exclusively to problems of mining geophysics.

An interesting overlap between mining and oil exploration is developing. Several mining companies now have important oil interests and several oil companies are apparently becoming interested in mining ventures.

Steps have been taken to bring all the vast exploration facilities and experience of the oil industry to bear on the problem of finding new sources of uranium and thorium to fill the needs of our rapidly expanding nuclear energy program.

The suggestion that this be done originated with the Atomic Energy Commission and the challenge was accepted by Dr. F. A. Lahee, formerly for many years chief geologist for the Sun Oil Company. Dr. Lahee is a man widely recognized for his untiring efforts for the American Association of Petroleum Geologists (of which he is a past president) and the American Petroleum Institute to advance the art of exploration. Typical of Dr. Lahee's energy and enthusiasm is the fact that he convinced the officers of the American Association of Petroleum Geologists, the Society of Economic Paleontologists and Mineralogists, and the Society of Exploration Geophysicists that the voluntary cooperation of the oil

industry in exploration for uranium under the free enterprise system is a patriotic undertaking that these societies should encourage. Under the chairmanship of Dr. Lahee a "Joint Advisory Committee on Radioactive Mineral Exploration" has been set up as a cooperative undertaking of the three societies with members of the committee drawn from all three societies and with Henry C. Cortes of Magnolia Petroleum Company—a past president of S.E.G.—as its vice-chairman.

Already in the space of a few months this committee has sent to oil companies and geophysical contractors suggestions for combining exploration for uranium and thorium with exploration for oil. These suggestions are so practical, and involve so little extra effort when combined with oil exploration, that several companies have begun to carry them out. Others may be expected to follow suit in the near future.

How does all this increased geophysical activity affect our professional responsibilities?

Certainly our ethical responsibilities are the same or somewhat emphasized. Those of us who deal with persons or firms who are using geophysics as an exploration tool for the first time have a high responsibility to guide them in the intelligent programming of operations and in the wise interpretation and use of the results. Those of us who are employed by firms with experience in the use of geophysical exploration have a high responsibility to justify the increased expenditures such firms are making in this expansion period by putting our best efforts into the gathering and interpretation of the increasing volume of data.

Ours has long been a heavy responsibility, together with our team-mates the exploration geologists, to insure a steady supply of raw materials to our world economy. Now it is a heavier one in the face of greater demands for old materials, and for such new materials as radioactive minerals, and the irreversible nature of the process of withdrawing these raw materials from the earth.

Dr. David Delo wrote a fine editorial entitled, "Professional Responsibility" in the July, 1952 issue of the A.G.I. News Letter. In it he stressed our professional responsibility to maintain adequate manpower in our profession. How well are we doing in this department? How great a problem do we have, in the first place, in maintaining our manpower at status quo?

Exploration Geophysics is relatively young, although more than a generation has elapsed since its pioneers first set out to supplement the efforts of exploration geologists. At its inception exploration geophysics was a young man's game (it still offers more incentive to a young man than most professions). However, while every recruit to exploration geophysics once meant one man added to the effective forces, now a substantial number of new recruits are necessary simply to balance deaths and retirements.

Inroads by government for military and technical needs are a drain on our manpower. These inroads have increased through one World War, the threat of another and the dragging-out of an energy-sapping so-called "police action."

It is no small task just to maintain the status quo.

What are the sources of additional manpower not only to hold the line but to expand our forces?

First, we should recognize that very few geophysicists are recruited from other professions. Occasionally we steal a few experienced and young graduate geologists from our exploration partners—simply "robbing Peter to pay Paul." In general we do well to avoid loss of men to various engineering professions, for they are as short of manpower as ourselves and are conducting strenuous recruiting campaigns. No, by far the best source of manpower for exploration geophysics, requiring a minimum of on-the-job training to fit our needs, are the graduate geophysicists and geophysical engineers (or "applied geophysicists").

Since 1947 the Society of Exploration Geophysicists has had a Committee on Geophysical Education, under the chairmanship of Father James B. Macelwane, commissioned to make an annual survey of the status of geophysical education. The last two surveys list the following degrees in geophysics or geophysical engineering as having been conferred in the United States and Canada:

Degrees	*1950–51*	*1951–52*	*% Decrease*
Bachelor's	170	97	43%
Master's	43	30	30%
Doctor's	22	15	32%

A study of the number of undergraduate students in the United States and Canada whose major is applied geophysics or geophysical engineering reveals that on the average only 73 bachelor's degrees will be granted each year for the next four years—a further decrease of 25 percent from the 1951–1952 figure.

Here, indeed, is cause for alarm! Our best source of recruits drying up in the face of our expanding needs!

We have some comfort in the facts presented in Father Macelwane's report that total enrollment in geophysical courses is up 10 percent between 1950–51 and 1951–52. In the face of the decreasing number of degrees conferred and expected to be conferred, this increased enrollment in geophysical courses must mean simply that more students with non-geophysical majors are being exposed to geophysics. This is good, but not as good as if we were increasing the number of graduates with full training in geophysics.

Will it be beneficial to us (as practicing geophysicists) to increase our manpower?

Do any of us feel that a shortage of trained personnel is a healthy situation? Are we worrying about the security of our jobs if, somewhere, we can tap a new source of manpower? I think not! Haven't we all felt the pinch of a shortage of help? I venture to say every geophysicist in this audience—particularly those exploring for oil—is working harder, putting in longer hours and having to spread his energy thinner today than five years ago. Such an increase in the volume of our work, if permitted to continue, could soon reduce us to the point of spending all our time on the routine details of our business and leave no time for the imaginative thinking which has always been the keystone of our success. Our

personal satisfaction with our jobs stems in large measure from this same creative work. Thus, for our own individual reasons we should do all we can to remedy the shortage of personnel our profession faces.

So, with the needs of our profession going hand in hand with our own personal desires, what can we do?

In a nutshell we must "make friends and influence people." A book by approximately this title was a best seller when it was written some years ago by Dale Carnegie. Its popularity, I believe, arose from the fact that it put its emphasis on "making friends." "Influencing people" followed naturally. If we realize, individually and collectively, that "making friends and influencing people" is the essence of good Public Relations we will better appreciate that oft misunderstood field. We will also understand "Public Relations" better if we realize it is not synonymous with "Publicity"—a word from which most scientists shrink. Good Public Relations first makes sure the objectives are sound; determines just what "public" or "publics" must be reached, considers the best ways and means and finally carries out these ways and means.

We have the objective:—increase our manpower.

We know the public we must reach:—university students, prospective university students and their advisors—their parents and teachers. These we must sell on the attractiveness of our profession as a career. Then there are university faculties, boards of regents and donors of endowments, grants, and scholarships. These we must enlist to provide curricula, equipment, and financial help for students.

We know what we have to sell:—our own belief in exploration geophysics as a way of life. I can express it for myself, though I am sure some of you can express it better. I feel an overpowering sense of satisfaction in being part of an exploration team; in knowing and being able to visualize the shape of things thousands of feet below me; in helping wrest well-hidden raw materials from a reluctant Mother Earth; and in helping devise new tricks to outwit this Mother Earth who seems to adopt new evasive tactics after every defeat. Furthermore, I like the life—a life of movement and activity; of hard work and satisfying accomplishments; a life on the front-line—on the scientific frontier. Finally, though only because I must make my list brief, I like the spirit of my fellow "doodle-buggers." We all have a common goal; a common challenge; common joys of achievement. We speak a common language denied to those on the outside; we are specialists and proud of our specialty.

Opportunities for advancement, inventive accomplishment, and exercise of initiative in exploration geophysics are still abundant—outstanding even in this day of changing frontiers. What young man of an ambitious and creative turn of mind could resist the opportunities the profession of exploration geophysics offers if he knew it as we know it?

Let's get busy and tell our story. No one is going to do it for us. We, after all, have the need and we have our enthusiasm to sell.

Where must we start? Right from scratch, I'm afraid. We travel almost incognito. Each of us has had the experience of having to spell the word "geophysicist" whenever in the course of daily life he was asked his occupation. You may have run into situations such as the one I talked myself into when I entered Canada three weeks ago.

When I was asked by the immigration officer what I was going to do in Canada I should have merely said I was a tourist but instead had to try and impress him and said "I'm going to make a speech in Toronto."

When I said this he closed his book and fixed me with a stern eye. "We don't need any propaganda on either Eisenhower or Stevenson here!"

"Oh," I said, "this isn't a political speech. I'm going to talk to the Society of Exploration Geophysicists!"

He relaxed: "Proceed, friend, I know it won't be a political speech. Neither the Democrats nor the Republicans could even spell that!"

To compete with other professions and occupations in attracting students into exploration geophysics, this expression and its companions "geophysicist," "geophysical prospecting," "seismograph," "gravity meter," etc., must become household and schoolroom words. Children, housewives and teachers are well acquainted with such titles as "doctor," "lawyer," "engineer," etc. You may be sure they are also familiar with the term "nuclear physicist"— in fact they could probably tell a pretty coherent story on how an atom bomb works from having read about it in newspapers, magazines, and even comic books. On the other hand we've a long way to go before a geophysicist, his life or his tools are as commonly discussed and understood.

There are reasons why this has been so. It its early phases geophysics was a jealously guarded secret insofar as methods and successes were concerned. Even now it suffers from its intimate relationship to the fierce competition for land acquisition. However, these reasons are no longer excuses for hiding our light under a bushel. We can talk freely about everything but the new instrument on the drafting board or this year's hot prospects.

Most of our thirty years of experiences may be drawn on to provide interesting conversation pieces. Our current operations can make spot news as soon as a discovery is made. Our way of life, our operations in headquarters in local communities, should be an open book. These things can't be hidden if we tried. Why make people think we have something to hide?

How can we best go about "making friends and influencing people"? We're proud of our activities; we're enthusiastic about our work. Opportunities abound for us to talk to people about our work over the back fence, at service clubs, church socials and in our Boy Scout activities, for example. These person-to-person contacts are our best line of approach. Talks before other explorationists, notices of meetings or reviews of papers in technical magazines or oil columns fail to reach the right people. We're talking to ourselves.

Now let's say we've caught the spark. We're making "geophysical prospect-

ing" household words. This is a long range job and will have long range results. Little Johnny, age 6, may be a geophysicist some day. What can we do to interest students nearer graduation?

Clearly we must help provide vocational guidance at the high school or first year of college level; we must encourage and help students once they have enrolled in courses of geophysics; we must encourage and help faculties and colleges in setting up adequate curricula and providing equipment for study; and we must get the graduates into geophysics instead of letting some of them wander off into other vocations.

Let us consider these problems one at a time. How are we doing in solving each?

In vocational guidance we are falling away below the potential demand we hope to build up. We are not even meeting current demands. Not a month passes by without the S.E.G. business office receiving at least one request from either a teacher or a student for information describing the requirements for and opportunities of a career in exploration geophysics.

I quote the reply of Colin Campbell, the S.E.G. Business Manager, to one such request:

"Dear Mr. Judd:

I regret very much that the Society at the present time has no prepared information for guidance in choosing the vocation of exploration geophysics.

We have ordered a supply of the brochure published by the American Geological Institute, entitled "Shall I Study Geological Science?" As soon as this material is received we will send you a copy.

Many thanks for your continued interest.

Cordially yours,"

This is a fine state of affairs, particularly when the A.G.I. booklet emphasizes geological rather than geophysical careers.

The only other geophysical vocational material of which I am aware is a brochure published by the U. S. Government as a guide to veterans wishing information on a career in geophysics. This booklet quotes salaries that are so far out of date that it probably scares away more students than it attracts.

The Society of Exploration Geophysicists recognizes this deficiency and has set up a project for its Public Relations Committee to prepare really adequate vocational guidance material in the field of exploration geophysics.

How are we encouraging students who have already enrolled as geophysical majors? To date this important activity has been left to the oil companies and various foundations, not exclusively interested in exploration, to carry on. The yield from these sources has been disappointingly small. For example, in the United States the National Science Foundation reports that out of 536 fellowships awarded in 1951 only 30 were awarded in geology and only two in geophysics while out of 38 at the postdoctoral level only 2 in geology and 1 in geophysics were awarded. From conversations with educators it is quite evident that this is a typical example.

The Society may be able to influence such giving indirectly. Perhaps Local Sections might set up scholarships or fellowships as their funds permit.

At least one major geophysical contractor is making an all-out effort to provide summer employment for geophysical students. The plan involves thorough indoctrination lectures including many by prominent geophysicists and executives outside this contractor's own organization. This is highly inspirational, but perhaps a more important part of the plan is that it permits the students actually to experience field operations and to rub shoulders with enthusiastic geophysicists on the job. We hope to have a comprehensive paper on this plan and the results thereof at the next Annual Meeting in Houston. If many more contractors and company-operated exploration departments would do as good a job, the problem of keeping up the interest of geophysical students would be solved.

Such summer employment programs also help increase student enrollment in geophysics. Word of such activity gets around. At least one university lists this summer employment plan in its catalogue.

These are activities of companies. The encouragement of papers on the subject which might inspire an extension of these activities is one of the functions of the Society of Exploration Geophysicists. Other activities of the Society are, or could be, the encouragement of Student Sections with continued aid in providing speakers and field trips for their programs; sponsorship of student essay contests; and encouragement or, perhaps, even sponsorship, of job procurement services.

But, as always, in Public Relations, we get back to the importance of the individual. I solicit your earnest thought on the possibility of trying out the "Buddy System" or, if you prefer, the "Big Brother System." If each of us who lives near one of our universities which teach geophysics would take the trouble to make a friend and confidant of at least one geophysical student we can be sure each such friend would complete his geophysical education. We could be sure he would have a better idea of what to expect of his job and what his job expected of him.

Anything that helps the students helps the educational institutions. In addition, universities may be aided by curriculum conferences and visiting lecturers by the S.E.G. and by research grants from industry encouraged by the S.E.G. Several Local Sections of the Society have donated or have been instrumental in obtaining donations from industry of geophysical libraries or equipment for universities. Here again, the Society is only as effective as its individual members. The job is for you and me.

As we observe the unprecedented increase in geophysical activity and the shortage of manpower to carry out this expansion adequately we find we have a professional responsibility to build up our source of manpower. Professional organizations, from the American Geological Institute, through the Society of Geophysicists on down to the Local Sections all have a part to play in the Public Relations campaign to reach and influence the public which is the source of our

manpower. Industry too has a part to play and has heavy stakes in the success of the campaign.

However, in the final analysis, we as individuals must accept the main responsibility to insure an adequate supply of manpower to help us meet the expanded demands we face. Fortunately we, individually, are best equipped to do this job. We are the ones who can say to our neighbor wherever he may be: "Exploration geophysics plays an important part in our nation's life. More geophysicists are sorely needed. I'm a geophysicist and I know the satisfaction and rewards are great. Your son would have a great future in Exploration Geophysics."

THE FORM AND LAWS OF PROPAGATION OF SEISMIC WAVELETS*

NORMAN RICKER†

ABSTRACT

An attack has been made upon the problem of the form of the seismic disturbance which proceeds outward from the explosion of a charge of dynamite and the laws of propagation of this disturbance. A mathematical theory was developed about ten years ago and a small amount of experimental work carried out at that time encouraged further efforts. Recently an extensive series of experimental researches have been carried out in a sensibly homogeneous shale section, and as a result of these studies a rather clear understanding of the form and nature of the primary seismic disturbance, and its laws of propagation, has been obtained for shale. The results are in good agreement with the theory.

INTRODUCTION

Among the various geophysical prospecting methods used in the search for petroleum, the seismic methods stand far ahead of the others in their ability to delineate buried geologic formation. These seismic methods have seen wide application to petroleum exploration and have been improved up to a certain stage during the period in which they have been in use. Attempts to obtain further improvement in seismic methods have met with quite serious obstacles some of which have not yielded to the customary experimental procedures of development.

About twelve years ago it was realized that some of the reasons for these difficulties lay in the very poor state of our knowledge of the basic principles of seismic wave propagation. In other words, the principal obstacle which lay in the path of further development appeared to be the fact that some of the basic problems of seismological physics had not been solved. One of these problems is concerned with answering the question: "What is the form of the seismic disturbance which proceeds outward from the explosion of a charge of dynamite in the earth and what are the laws of propagation of this disturbance?" This problem has lain unsolved during the history of seismology in spite of its basic importance. Questions relative to seismic resolution and the precise delineation of reflecting beds cannot be attacked properly until this question is answered.

A serious attack upon this problem was started about twelve years ago, and through mathematical researches a solution was obtained which seemed to be in accord with the small amount of experimental work carried out at that time. These mathematical studies resulted in what is now known as *The Wavelet Theory of Seismogram Structure*. Parts of this theory have been published.

* Presented before the Third World Petroleum Congress, The Hague, 1951. Manuscript received by the Editor October 1, 1952.

† Senior Research Physicist, Research Laboratories, The Carter Oil Company, Tulsa, Oklahoma.

To summarize the results of the theory, it has been found that the classical wave equation

$$\nabla^2\Phi = \frac{1}{c^2}\frac{\partial^2\Phi}{\partial t^2} \tag{1}$$

is not sufficient properly to explain seismic phenomena, and that it is necessary to make use of a modified wave equation

$$\nabla^2\left[\Phi + \frac{1}{\omega_0}\frac{\partial\Phi}{\partial t}\right] = \frac{1}{c^2}\frac{\partial^2\Phi}{\partial t^2} \tag{2}$$

which, in its plane wave form, was first given by Professor George Gabriel Stokes in 1845. Solutions of equation (2) have been given in the author's previous papers to describe the earth-displacement, the earth-particle velocity, and the earth-particle acceleration as a function of time and distance.

At the Rice Institute meeting of The American Physical Society in November, 1947, the following integral representations of the displacement and earth-particle velocity were given and are published herewith for the first time.

The displacement function is

$$\dot{\Phi} = \frac{2}{R}\int_0^\infty \beta e^{-R\beta(1+\beta^2)^{-1/4}\sin(\tan^{-1}\beta/2)} \cdot\sin\left[R\beta(1+\beta^2)^{-1/4}\cos\left(\frac{\tan^{-1}\beta}{2}\right) - \beta T\right]d\beta \tag{3}$$

and the velocity function is

$$\ddot{\Phi} = -\frac{2}{R}\int_0^\infty \beta^2 e^{-R\beta(1+\beta^2)^{-1/4}\sin(\tan^{-1}\beta/2)} \cdot\cos\left[R\beta(1+\beta^2)^{-1/4}\cos\left(\frac{\tan^{-1}\beta}{2}\right) - \beta T\right]d\beta. \tag{4}$$

The quantities R and T are dimensionless and are called the numerical distance and numerical time respectively. They are defined by

$$R = \frac{\omega_0 r}{c} \tag{5}$$

$$T = \omega_0 t \tag{6}$$

wherein r is the true radial distance, c the classical velocity of propagation, given by the square root of the elasticity over the density, and t is the time. ω_0 is the constant occurring in equation (2).

Since

$$\ddot{\Phi} = \frac{\partial\dot{\Phi}}{\partial T} \tag{7}$$

if we represent the actual displacement by $\dot{\Phi}$ it follows that the actual earth-particle velocity is

$$\frac{\partial \dot{\Phi}}{\partial t} \quad \text{or} \quad \omega_0 \ddot{\Phi}. \tag{8}$$

Equations (3) and (4) represent the seismic behavior of the earth when the displacement at the shot point is a simple impulse, that is to say, at the position of the explosion the walls of the cavity move outward and back in a very short interval of time. This behavior is illustrated in Figure 1 wherein the various wavelet forms have been drawn as functions of the numerical time, T.

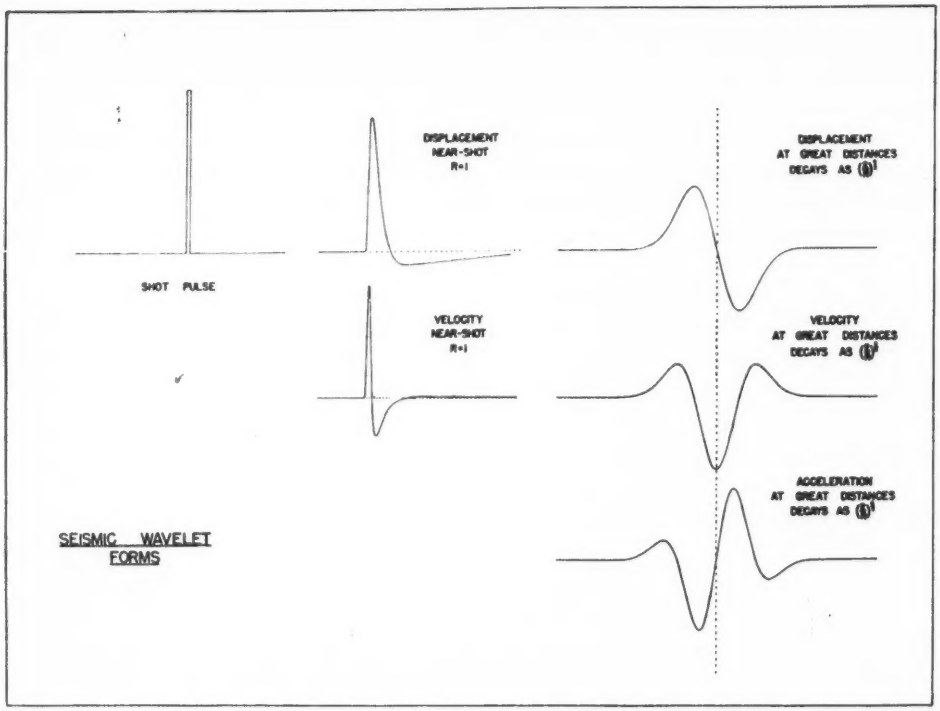
SHOT PULSE
DISPLACEMENT NEAR-SHOT R=1
DISPLACEMENT AT GREAT DISTANCES DECAYS AS (1/R)
VELOCITY NEAR-SHOT R=1
VELOCITY AT GREAT DISTANCES DECAYS AS (1/R)
ACCELERATION AT GREAT DISTANCES DECAYS AS (1/R)
SEISMIC WAVELET FORMS

FIG. 1. Shot pulse and propagated wavelet forms.

We may also write the displacement, velocity and acceleration functions as

$$\dot{\Phi} = \left(\frac{2}{R}\right)^{4/2} \mathcal{U}(u \mid R) \tag{9}$$

$$\ddot{\Phi} = \left(\frac{2}{R}\right)^{5/2} \mathcal{V}(u \mid R) \tag{10}$$

$$\dddot{\Phi} = \left(\frac{2}{R}\right)^{6/2} \mathcal{W}(u \mid R) \tag{11}$$

wherein

$$u = \frac{T - R}{\left(\frac{R}{2}\right)^{1/2}}. \tag{12}$$

$\mathcal{U}(u|R)$, $\mathcal{V}(u|R)$, and $\mathcal{W}(u|R)$ are called wavelet-form functions and are drawn as functions of u with R held fixed as a parameter. In Figure 2 a number of the wavelet forms

$$\mathcal{V}(u|R)$$

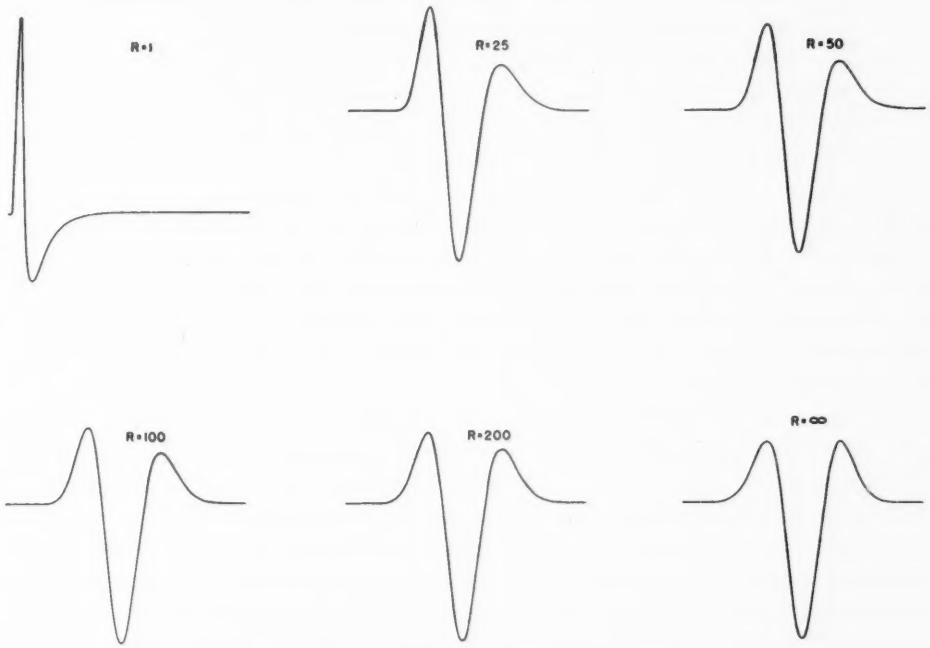

FIG. 2 Computed velocity-type wavelet forms.

are shown. These forms have been described in the published papers. They represent the motion of the trace of an electrical seismograph which is responsive to the velocity of earth-particle motion, and which is free from distortion. It is possible, then, to make a critical comparison of forms obtained experimentally with these forms computed from the theory.

The are also a number of laws of wavelet propagation derived from the theory and with which experimental observations may be compared:

1. It is the center of the wavelet which travels with the velocity, c, given by the square root of the elasticity over the density. This, in fact, defines the wavelet center.

2. The breadth of the wavelet, measured in seconds, say, is proportional to the square root of the propagation time of its center, the law holding for all three forms $\mathcal{U}, \mathcal{V}$, and $\mathcal{W}$.
3. The amplitude of the $\mathcal{U}$ type wavelet is proportional to the minus 4/2 power of the travel time of its center. This is for spherical waves spreading out from the center of the disturbance.
4. The amplitude of the $\mathcal{V}$ type wavelet is proportional to the minus 5/2 power of the travel time of its center. This also is for spherical waves spreading out from the center of the disturbance.
5. The amplitude of the $\mathcal{W}$ type wavelet is proportional to the minus 6/2 power of the travel time of its center. This again is for spherical waves spreading out from the center of the disturbance.
6. The amplitudes of the displacement earth-particle velocity and earth-particle acceleration are proportional to the 5/6 power of the mass of the charge, the charges being spherical, and the explosion pressure being independent of size of charge.

A number of other workers have appreciated the importance of energy losses in problems of seismic wave propagation, among whom may be mentioned H. Nagaoka, H. Jeffreys, K. Sezawa, and B. Gutenberg. An interesting investigation of the disturbance quite close to the explosion has been made recently by J. A. Sharpe, using classical elastic solid theory and without considering absorption. His results, however, do not account for the manner in which the disturbance propagates outward.

Relative to the importance of Stokes' equation (equation 2), it should be stressed that it is never possible to neglect the dissipation term $1/\omega_0 \partial/\partial t$, however great the value of ω_0, since this term contributes toward the shaping of the wavelet form and toward determining its laws of propagation.

Attention should also be called to the very different manner in which these transient wavelet forms decay as they advance, as compared with the decay of continuous sinusoidal waves. Solutions of Stokes equation for continuous sinusoidal waves decay exponentially with the time of travel, maintaining their uniform cycle breadth as they advance. On the other hand, the displacement, earth-particle velocity, and earth-particle acceleration forms, $\mathcal{U}(u|R)$, $\mathcal{V}(u|R)$ and $\mathcal{W}(u|R)$ decay in accordance with the $-4/2$, $-5/2$, and $-6/2$ powers respectively of the travel time, and the three forms all broaden with the square root of the travel time.

EXPERIMENTAL STUDIES

Recently a rather extensive series of experimental studies have been carried out with the objective of determining the true form of the seismic disturbance which travels outward from the explosion of a charge of dynamite as a point in the earth. In order to carry out satisfactory experimental researches of this nature, it is of fundamental importance that the studies be conducted in a very simple earth, as nearly homogeneous as can readily be obtained. This is necessary

in order that the seismograms may have as few disturbances as possible. Seismograms obtained from studies in the average severely bedded earth are far too complicated from the overlapping of successive disturbances to permit very much basic research information being obtained from them. The selection of such a simple homogenous and isotropic earth is not easy. The best choice to the knowledge of the author is the thick section of Pierre shale in the Denver basin in the eastern part of the State of Colorado. In this basin the shale, which is of Cretaceous age, ranges in thickness from 0 to around 8,000 feet. It lies exposed at the surface over a considerable area. At places it is covered by more recent Cretaceous beds of

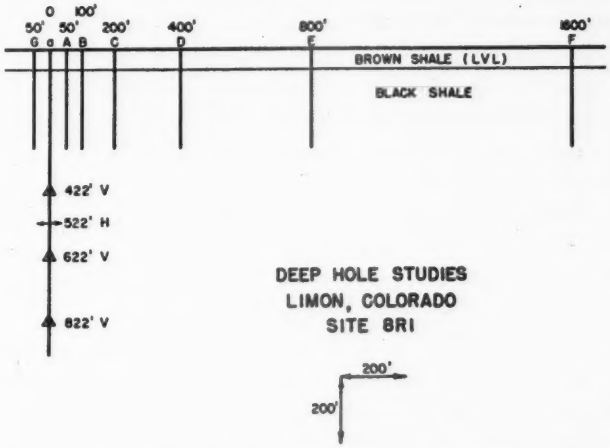

FIG. 3. Disposition of shot holes for the studies at Limon, Colorado.

Fox Hills sandstone or Laramie formation and at other places by a Tertiary gravel conglomerate known as the Ogalalla.

Two different sites were occupied in the Pierre shale, one about three miles north of Limon, Colorado, and the other about thirty-seven miles north of Limon at the crossroads village of Last Chance. At both of these sites the Pierre was exposed at the surface. At both sites the terrain was reasonably flat, the Limon site lying upon a ridge and the Last Chance site lying in a valley. In drilling into this shale, the bit first encounters a brown shale which is dry and which breaks easily. At a depth of about 55 feet (at Limon) the bit breaks suddenly into a black shale which is wet and somewhat soft at the top, but which firms rapidly so that it is quite hard at depths greater than, say, 100 feet. The upper crust of brown shale is lithologically the same as the underlying black shale and represents merely the dried and oxidized zone above the water table. The base of this brown shale was found to lie but very slightly above the base of the low velocity layer.

Figure 3 shows, in section, the disposition of holes drilled into the shale at Limon for the purpose of the experimental studies. A deep hole was drilled with a five inch drag bit and in this hole there were placed three vertical component geophones at depths of 822 feet, 622 feet, and 422 feet. These geophones had na-

tural frequencies of $3\frac{1}{2}$ cycles per second, were damped to $\frac{1}{4}$ of critical damping, were clamped securely to the sidewalls of the bore hole, and each geophone had its separate cable to carry its signals to the surface. Before being placed in the hole, the geophones were carefully calibrated by dropping a small steel ball of known mass from a measured height and letting it fall into a small cup of grease placed on top of the geophone. By making a recording of the resulting disturbance for a known amplifier setting, the resulting trace amplitude could be compared with the velocity given the geophone case, calculated by the conservation of momentum, and so the sensitivity could be determined. The geophone was suspended from long rubber bands for this sensitivity determination.

The geophones formed part of a completely calibrated flat-response, distortion-free electrical seismograph, by means of which precise determinations of earth-particle velocities in centimeters per second could be obtained from measurements of trace amplitudes. A horizontal component geophone was also placed in the hole at a depth of 522 feet as shown in the figure.

The recording oscillograph was especially designed for the studies and contained a drum seventeen inches in diameter with a face wide enough to take a strip of eight inch photographic recording paper about fifty inches long wrapped once around the drum and held in place by clips. The drum rotated on ball bearings and was brought up to any desired speed by means of a hand-operated crank. When brought up to speed it was allowed to coast along on its own momentum. Since the friction was quite low, the paper speed was exceptionally uniform. In order to be able to place the seismogram on the strip of photographic paper in the proper position, the charge was fired in synchronism with the drum's rotation. This was accomplished by placing a relay in series with the shooting circuit, this relay being controlled by a micro-switch, cam-operated by the rotating drum. Thus the charge was fired, not at the time the shooter closed his switch, but at a short time thereafter when the camera drum was in the proper position to receive the seismogram. A shutter, similarly operated, remained open for but one revolution of the drum while the seismogram was being recorded.

The galvanometers in the camera were of the d'Arsonval type with natural frequencies around one thousand cycles per second and were damped to 7/10 of critical damping. Attention was also given to linearity of trace motion with respect to signal amplitude.

The frequency characteristic of the amplifiers was very flat, well beyond the range of frequencies of the seismic studies, and there was no measurable phase variation with respect to frequency throughout the range of interest. The amplifiers had calibrated input attenuators so that the over-all magnification of the seismograph from amplitude of earth-particle velocity to amplitude of trace motion was known for any setting of the attenuator.

Time lines were placed on the seismogram by flashes of light through a slotted wheel driven by a synchronous motor operating from a 1,000 cycle standard frequency generator. There were placed on the seismogram 1,000 timing

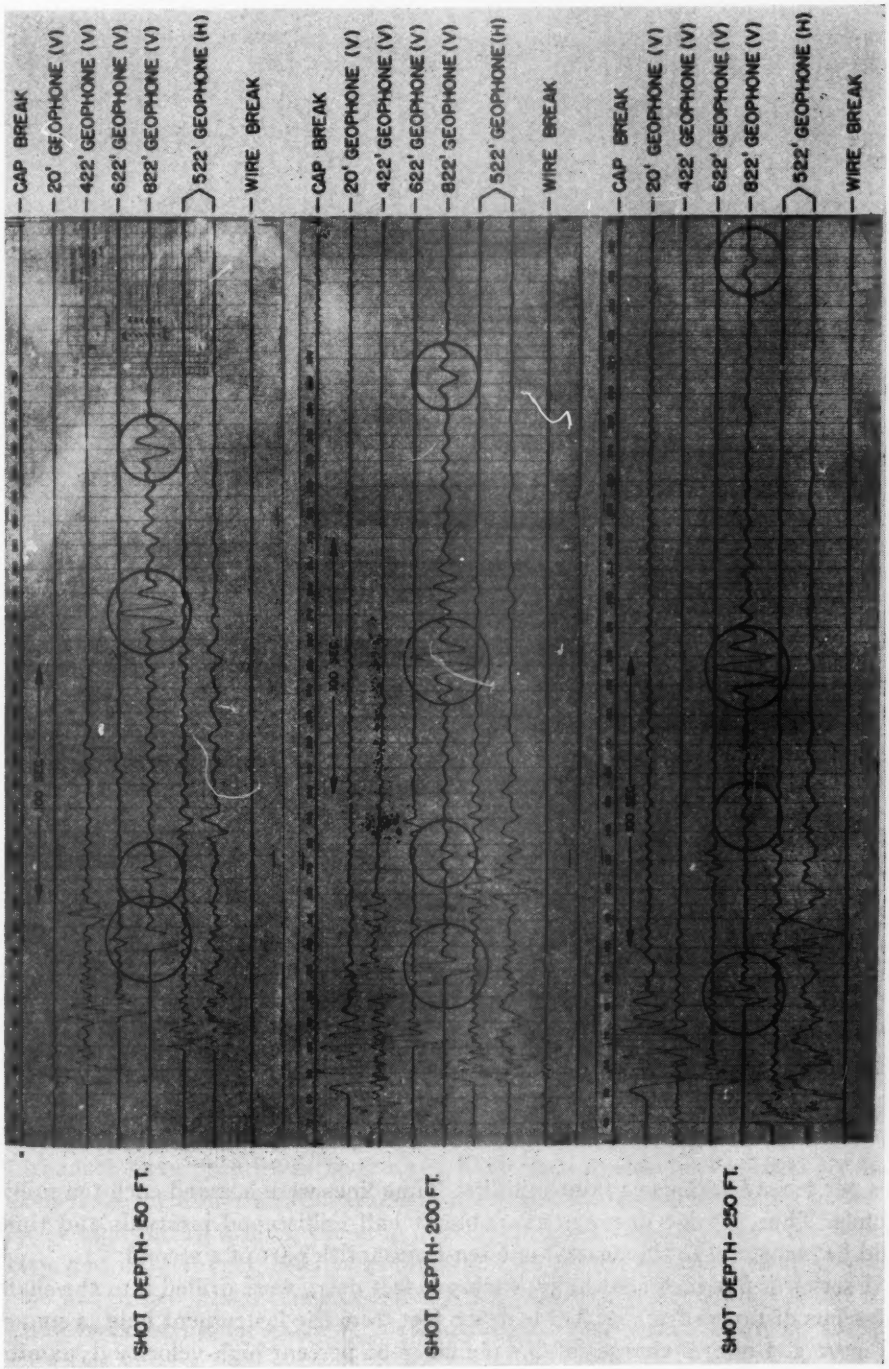

FIG. 4. Three typical seismograms made in Pierre shale.

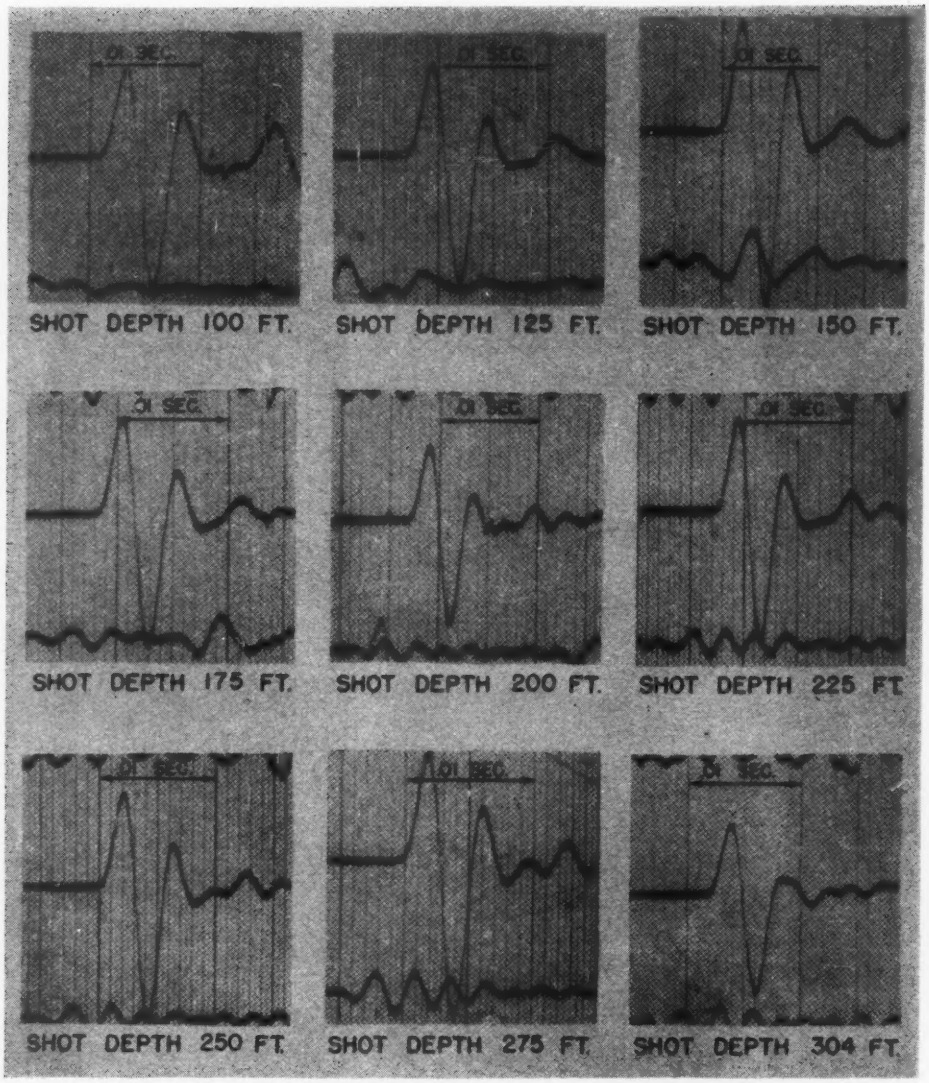

FIG. 5. The primary seismic disturbance, velocity type, as observed in Pierre shale.

lines per second and also a faint mid-line. Time lines were heavied each ten milliseconds. Thus, a time line was available at half-millisecond intervals and time could be measured to the nearest one ten-thousandth part of a second.

A series of five inch shot holes, each 310 feet deep, were drilled into the shale at various distances from 50 feet to 1,600 feet from the instrument hole as shown in Figure 3. Uniform charges of one pound of 60 percent high-velocity dynamite were fired in these shot holes at depths varying in steps of 25 feet throughout

the length of each shot hole. Thus, a large number of seismograms were obtained and these seismograms have enabled a large number of measurements to be made of the primary disturbance and other disturbances on the seismograms.

In Figure 4 there are shown three typical seismograms made at the Limon, Colorado, site. On each of these seismograms four prominent disturbances are shown circled. The first is the primary disturbance with which we are concerned in this paper. The second is the disturbance which started upward, was reflected from the base of the low velocity layer and then traveled downward to the geophone. The third disturbance contains both the shear wave and a tube wave which interfered with it (see Sharpe 2). The fourth disturbance is paired with the third through a reflection from the base of the low velocity layer.

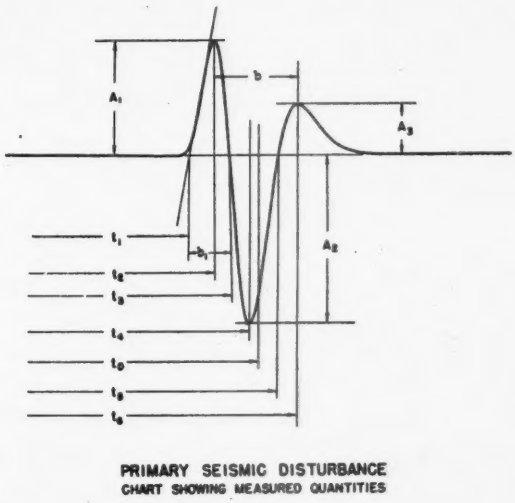

FIG. 6. Primary seismic disturbance—chart showing quantities measured.

In Figure 5 there are shown nine enlarged forms of the primary disturbance as delivered by the 822 foot geophone and initiated by shots at varying depths in the shot hole, A, placed 50 feet from the instrument hole. It will be noticed that the small disturbances which follow the form vary from seismogram to seismogram while the principal disturbance retains a fairly constant shape. The minor disturbances have been investigated and have been found to be caused by reflections from the minor stratifications in the shale. The shale, of course, is not perfectly uniform. In drilling the deep instrument hole, a careful log of the hole was kept and only twenty beds were found throughout the 1,005 feet to which the hole was drilled which could be called harder than the general body of the shale. These beds of harder calcareous shale ranged from one inch to ten inches in thickness.

Figure 6 shows the measurements which were made on the primary disturb-

ance. It will be noticed that no attempt has been made to measure a *first kick* arrival time in the conventional manner. This is because there is no sudden *takeoff* of the trace when the disturbance arrives. The motion begins gradually and if a *first kick* arrival time is attempted, the time picked will depend upon the

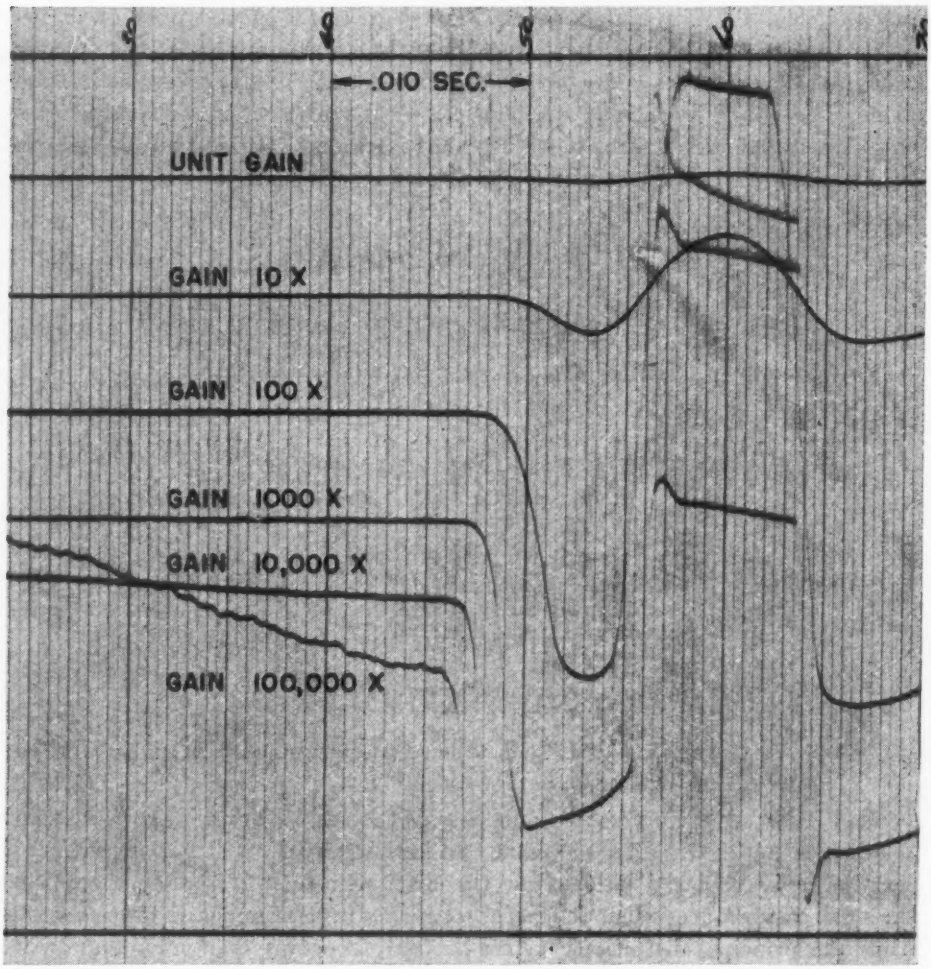

FIG. 7. Seismograms from six amplifiers, all on the same geophone but with gains increasing by factors of ten.

over-all magnification of the seismograph. This is demonstrated on Figure 7 which shows the traces of six amplifiers whose gains vary in steps of ten-fold increase in gain, all amplifiers being driven by the same geophone. It will be seen that the conventional *first kick* moves ahead about one millisecond for each ten-fold increase in magnification. This is for a wavelet breadth of about ten milli-

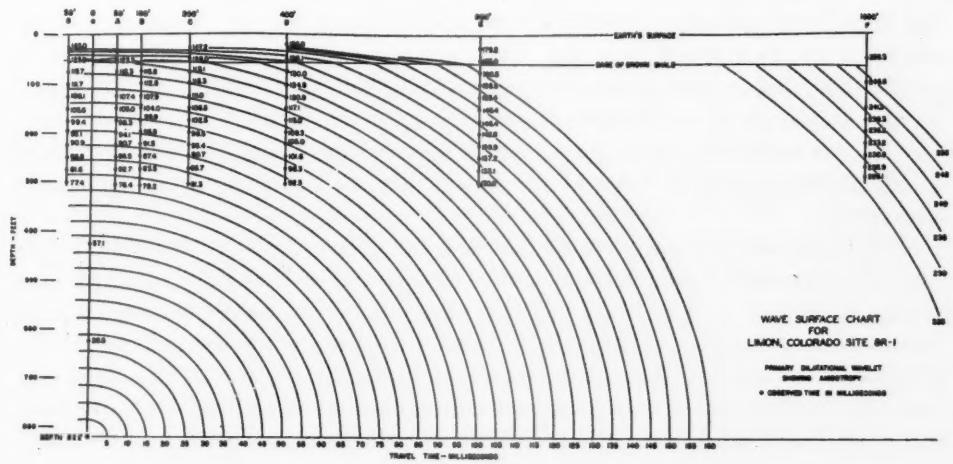

FIG. 8. Wave surfaces for propagation in the Pierre shale at Limon, Colorado.

seconds. In place of the *conventional first kick* the time t_1 is substituted. This time, called the *intercept first kick* is obtained by picking the time where a tangent drawn to the first motion through the point of inflection intersects the time axis. This point does not advance as the amplification of the seismograph is varied. The other time picks t_2, t_3, t_4, t_5, and t_6 are made on the successive bend points and axial crossings of the form. The time t_0 is the arrival time of the *wavelet center*. At great distances, after all dispersion has disappeared and the form has become symmetrical, t_4 and t_0 are coincident. In the plotted data, the arrival time of the disturbance is taken as t_4 because it is reasonably near the wavelet center. The amplitudes measured are indicated as A_1, A_2, and A_3 on Figure 6. The breadth of

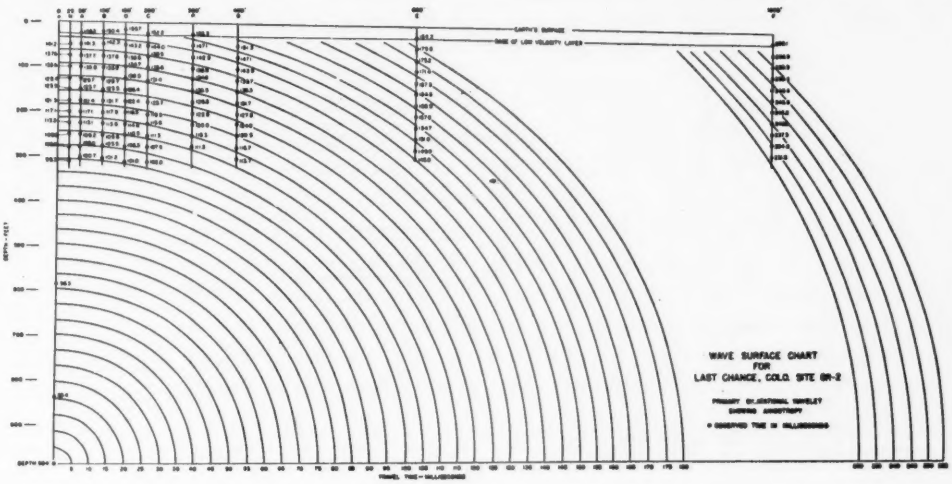

FIG. 9. Wave surfaces for propagation in the Pierre shale at Last Chance, Colorado.

the form is the quantity, b, representing the difference (t_6-t_2). Since very often the form was overlapped by a later disturbance, measurements of the early parts of the disturbance were generally the most reliable. Accordingly, A_1 was taken as the amplitude of earth-particle velocity, and the breadth b_1 given by $b_1=(t_3-t_1)$ was measured. Since, for a form of given shape b could be obtained from b_1 by multiplying by a factor of proportionality, the quantity b_1 was generally measured.

Figures 8 and 9 show the wave surfaces for propagation in the shale. These surfaces were constructed as follows. Having determined that there was no measurable difference in time when shot and geophone were reversed in position, the shot was considered as lying at the position of the deep geophone and the arrival times were assigned to the points actually occupied by the shots. The wave surfaces drawn through the data points are true ellipsoids and conform very precisely with the arrival time data. The smoothness of the data is evidence of the suit-

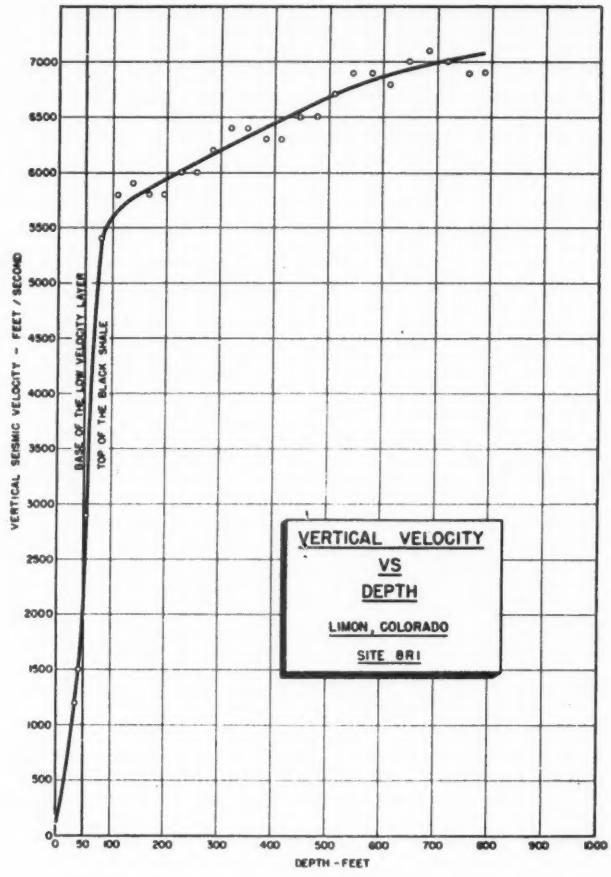

FIG. 10. Wavelet velocity as a function of depth—Pierre shale, Limon, Colorado.

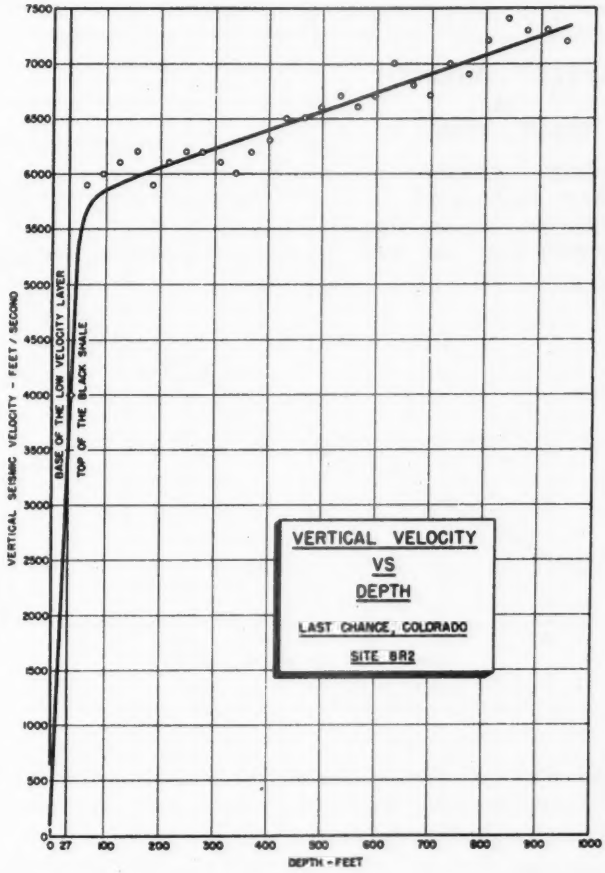

FIG. 11. Wavelet velocity as a function of depth—Pierre shale, Last Chance, Colorado.

ability of the shale as a medium for the studies. Such smooth surfaces cannot be drawn in a more severely bedded earth.

The anisotropy was such that horizontally traveling dilatational disturbances had a higher velocity of propagation than vertically traveling disturbances by about 18 percent at Limon and by about 14 percent at Last Chance.

The ray paths are but slightly curved, the centers of curvature lying in a horizontal plane about 3,000 feet above the earth's surface.

Figures 10 and 11 show the velocity of vertically traveling dilatational waves as a function of depth in the earth for the Limon and Last Chance areas respectively. These curves were prepared from interval times and interval distances taken from the wave surface charts. Very low values of the velocity are reached near the earth's free surface. Since the earth at the very surface should have the elasticity of air and the density of earth, it may readily be seen that these velocities may drop to as low a value as 100 feet per second.

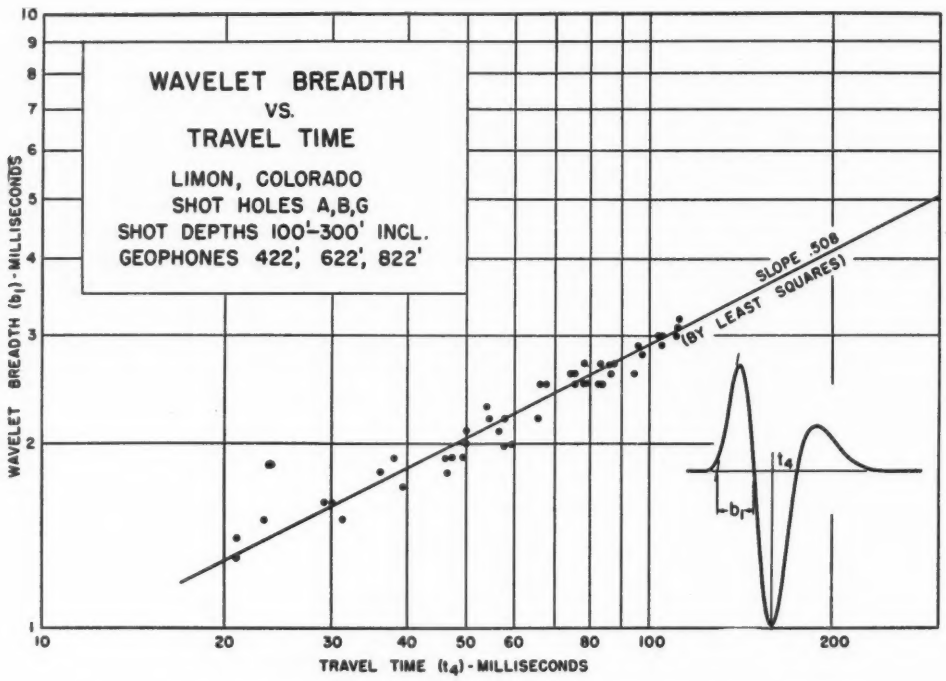

FIG. 12. Wavelet breadth as a function of travel time to reveal rate of broadening law.

Figure 12 shows the manner in which the breadth of the disturbance varies with the travel time, the plot being made on logarithmic paper, and drawn for the Limon area. The straight line drawn through the data points by a least square technique has a slope of 0.508. A similar plot for the Last Chance area had a slope of 0.498. Since, according to the wavelet theory, this slope should be $\frac{1}{2}$ it may be seen that the rate of broadening law is very closely satisfied.

In order to study the form of the disturbance properly, it is necessary to have some standard of comparison. The wavelet theory provides such a standard of comparison in the forms calculated from the theory. Some of these forms are given in Figure 2. Now the numerical distance, R, which is a parameter of the series of forms, may be determined for the observed forms from the approximate relation

$$R = \sqrt{\frac{10}{\left(\frac{A_1}{A_2} - .446\right)^3}}.$$

It was found that, for the observed forms, R ranged from 5 to 32. Since the only computed form in this range is that for $R=25$, the forms selected for comparison are those whose numerical distance fell reasonably close to 25. One comparison is shown in Figure 13. It will be seen that the fit between observed and

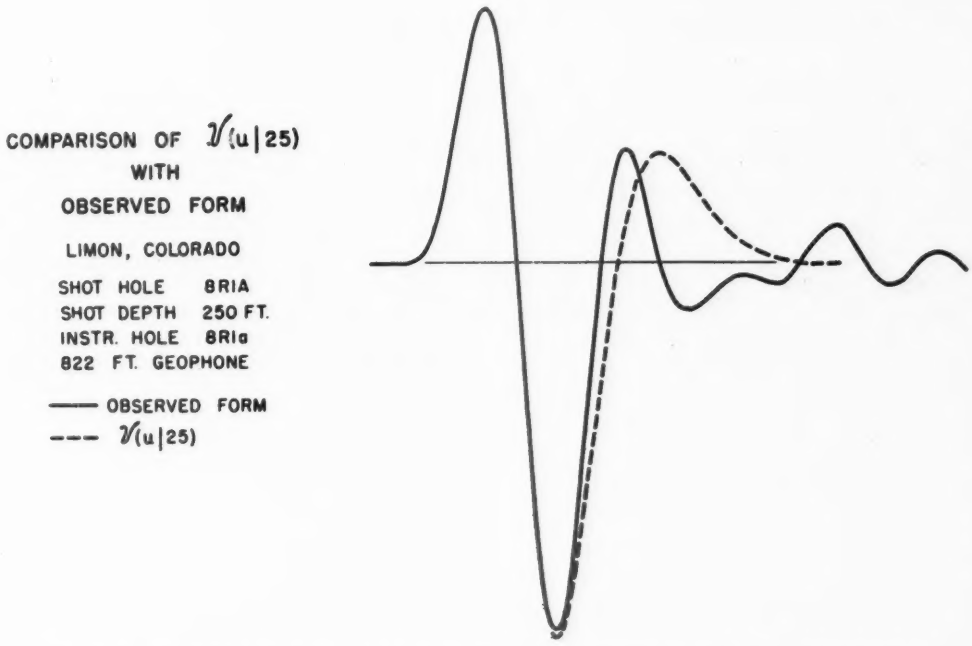

FIG. 13. Showing good fit of observed form to computed wavelet form up to second bend point.

theoretical forms is excellent up to the second bend point. On Figure 14 twelve additional comparisons are shown and in addition, the residual obtained by subtracting the ideal form from the observed form is drawn in. Very often this residual has a beginning very much like another wavelet form.

In Figure 15 a more complex disturbance, obtained in the Last Chance Area, has been broken down into three wavelet forms, each of numerical distance 25, each of a lesser amplitude than its predecessor and with the centers equally spaced. This suggests that the shock created by the explosion may not be a single impulse but a succession of impulses equally spaced in time, similar to the *bubble pulses* obtained by Ewing for shots made in open water. The interval of $3\frac{1}{2}$ milliseconds between shocks, however, is too small for gravity controlled bubble pulses and suggests that an elastic rebound of the walls of the shot cavity is causing a succession of slaps and so creating the multiple impulses.

Another important matter to investigate is the spectrum of the observed form and its comparison with the spectrum predicted by the wavelet theory. In order to make this comparison a number of the observed forms were analyzed by means of a Henrici rolling sphere harmonic analyzer and some of the analyses are shown on Figure 16.

The first form is the theoretical form $\mathcal{V}(u|25)$ and below it is the analysis made of it by the harmonic analyzer, the solid circles representing measured values of amplitude of the harmonic components. The dashed line is the wavelet

FIG. 14. Comparisons of observed forms with computed velocity-type wavelet form.

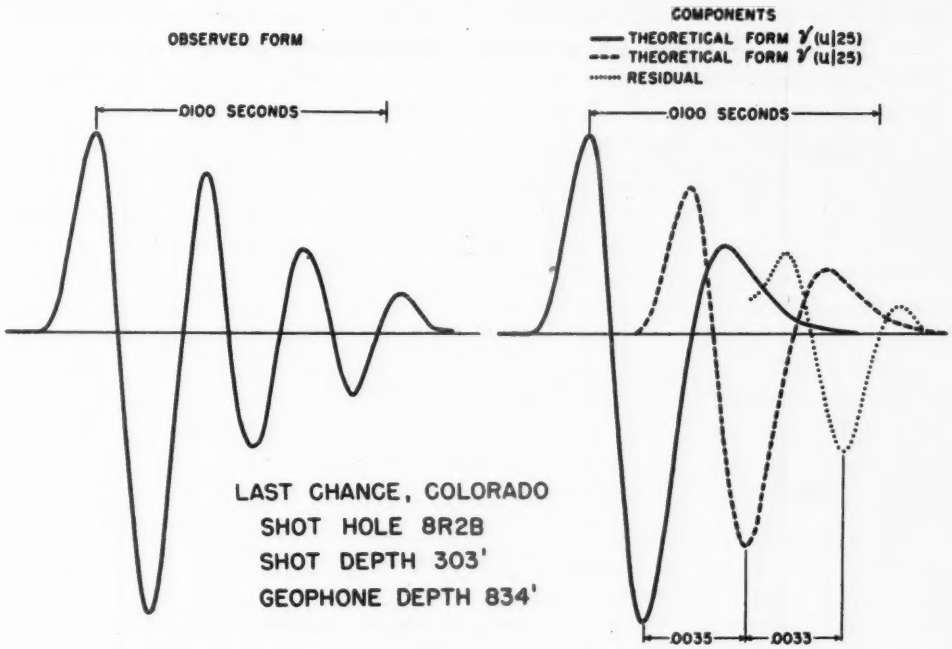

FIG. 15. Breakdown of observed wavelet-complex into its wavelet components.

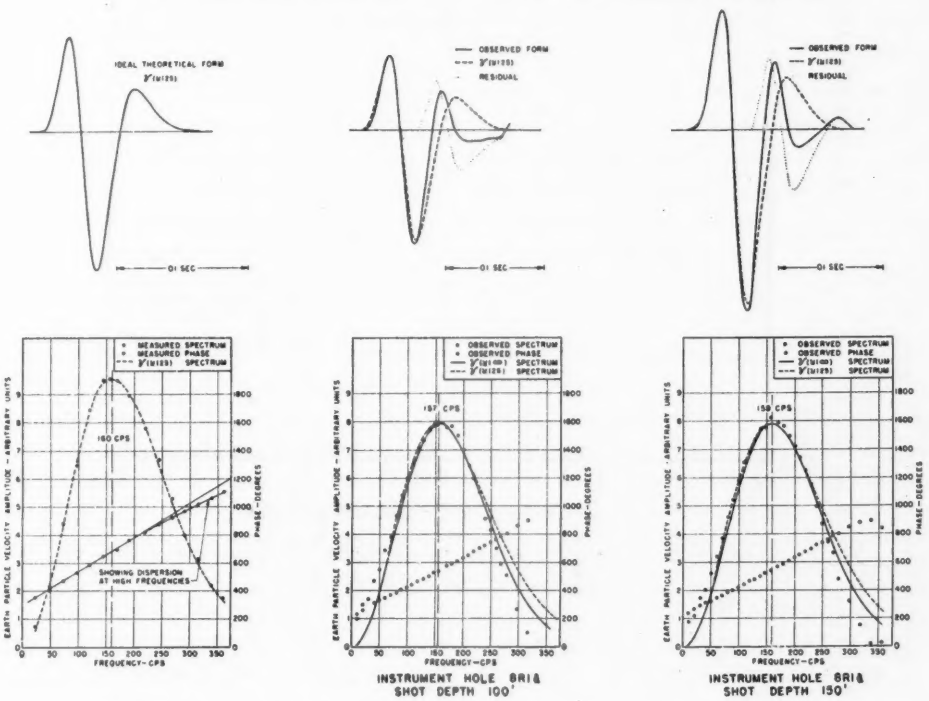

FIG. 16. Comparison of measured spectra with the theoretical spectral curve.

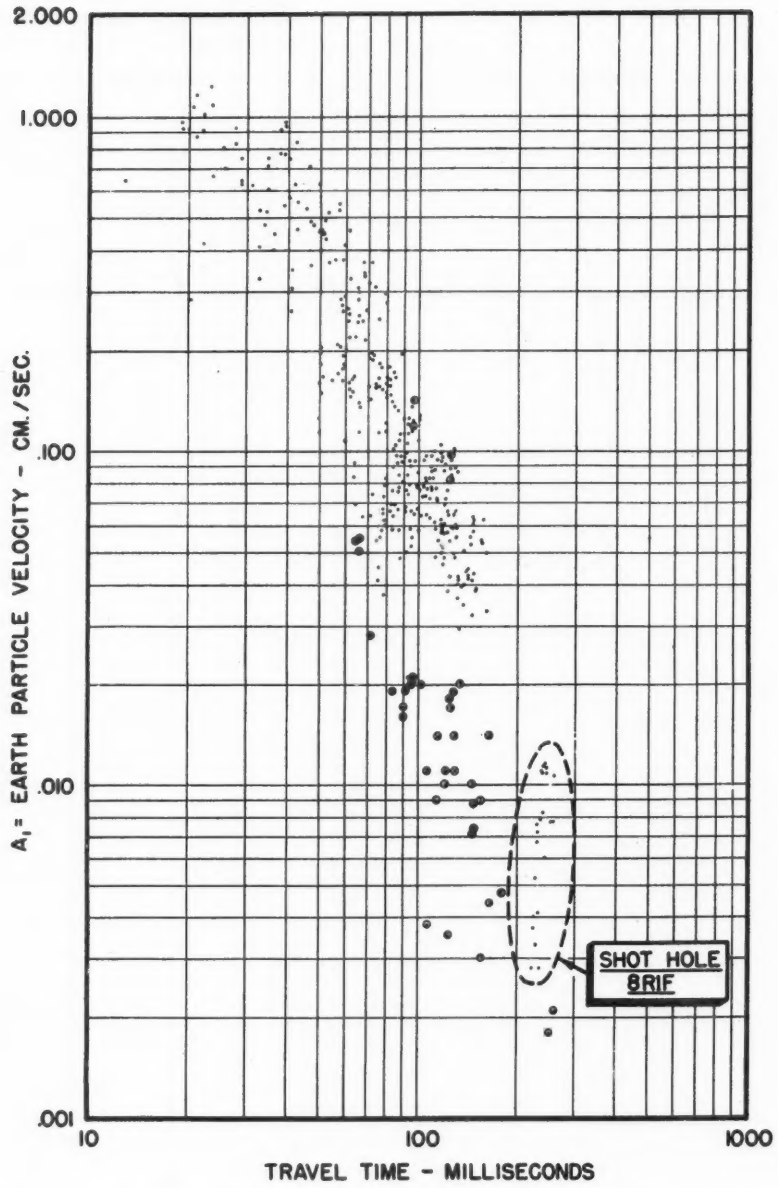

FIG. 17. Amplitude of earth-particle velocity plotted against the travel time for all data obtained at the Limon, Colorado site.

spectrum as plotted from its equation. The purpose of this comparison is to show first the precision with which the analyzer is able to measure the spectrum, and it may be seen that the points are well placed with respect to the theoretical curve. The open circles represent the measured phase while the solid line through these points was drawn from the theoretical expression for the phase. With the assurance, then, that the analyzer is able to make precision amplitude and phase measurements of the forms, the analyses of the other two forms are to be studied. In these other two graphs the measured spectra of the two observed forms are compared with the spectra of $\mathfrak{V}(u|\,25)$ and $\mathfrak{V}(u|\,\infty)$. It is apparent that the agreement is good, but that the precision is not sufficient to determine the numerical distance of the form from its spectrum.

An important part of the studies was the determination of the law of decay in amplitude of the earth-particle velocity with increasing travel time of the disturbance. On Figure 17 there are shown all the data points obtained in the Limon area, with the amplitude A_1 plotted against the travel time on logarithmic paper. There is a very considerable scatter but it must be remembered that although the charge is held constant at one pound there are three geophones at different depths, and shots at twelve different depths in six shot holes at varying distances from the instrument hole. Also, the circled points represent data from shots in the friable brown shale low velocity zone. A study of the data indicated that the greatest cause of this scatter was varying shot depth. Accordingly the data were replotted so that on each graph the shot depth was held fixed. The results are shown on Figure 18 for the Limon Area and on Figure 19 for the Last Chance Area. On each of the graphs a straight line has been drawn through the data points by least square adjustment. The slopes of these lines range from minus 2.19 to minus 2.90 for Limon and with an average value of minus 2.42. For the Last Chance area the slopes range from minus 2.18 to minus 2.96 with an average value of minus 2.43. The averages differ from the minus 2.50 given by the wavelet theory by only 3 percent. It may then be safely concluded that the experimental data agree quite satisfactorily with the theory.

In order to investigate the effect of varying shot depth the upper tier of graphs shown on Figure 20 were drawn. Here each graph is for a separate shot hole. In a given shot hole twelve shots have been fired at different depths. Consider a single shot. There are three data points associated with this shot from the observations made by the three geophones. Through these three data points the best straight line of slope minus 5/2 has been drawn by least square adjustment. These lines do not coincide but stand at different heights for a specified travel time. This is because the several shots are not equally effective as a seismic source. If we extrapolate along any line to a travel time of one second, the amplitude at that time is a measure of the strength of the shot. We call this the *seismic punch*. This seismic punch may be determined for any observation by forming the product $A_1 t_4^{5/2}$. In the second tier of graphs of Figure 20 this seismic punch has been plotted as a function of shot depth for each of the shot holes. It

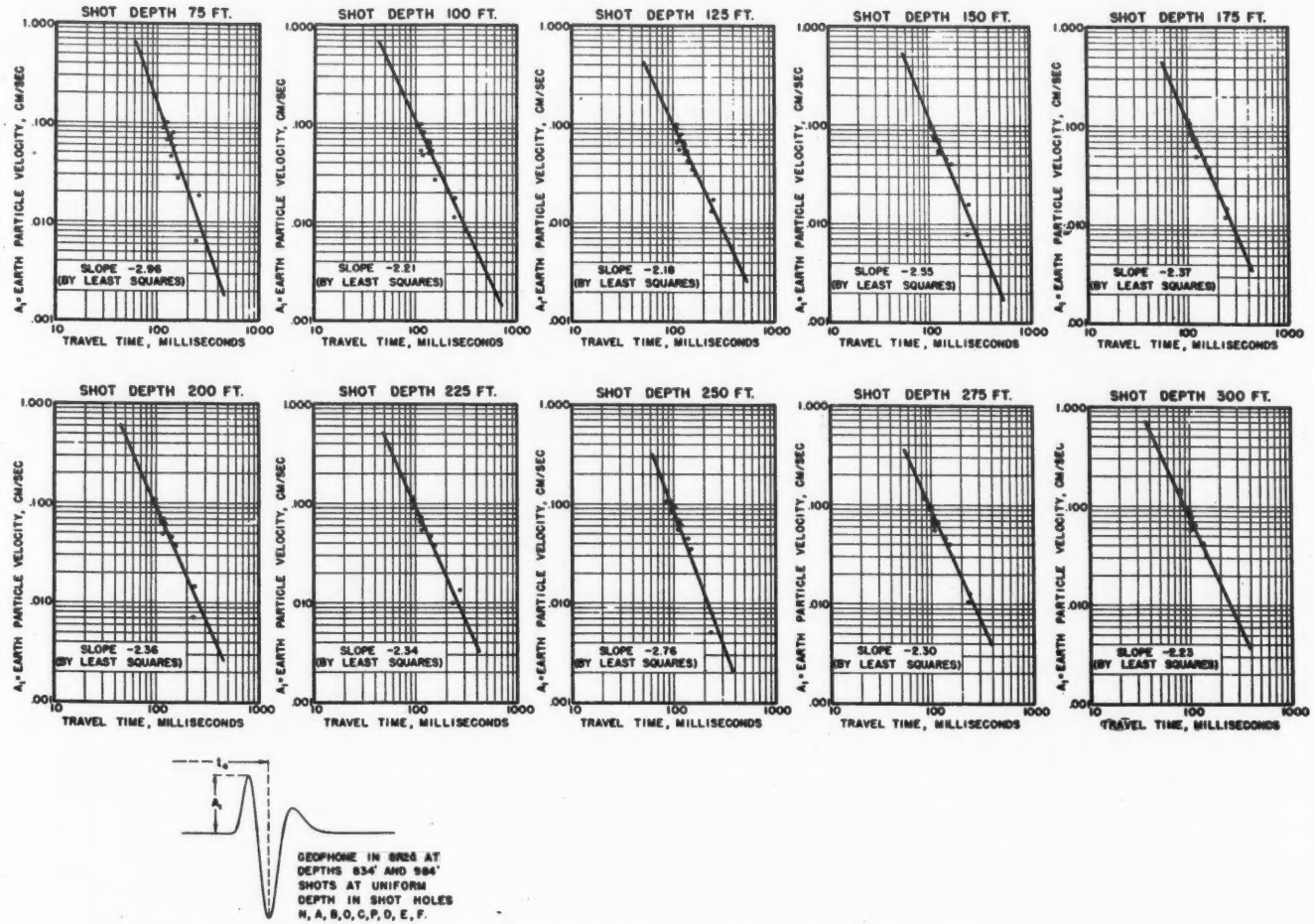
SHOT DEPTH 75 FT.
SLOPE -2.96 (BY LEAST SQUARES)
SHOT DEPTH 100 FT.
SLOPE -2.21 (BY LEAST SQUARES)
SHOT DEPTH 125 FT.
SLOPE -2.18 (BY LEAST SQUARES)
SHOT DEPTH 150 FT.
SLOPE -2.55 (BY LEAST SQUARES)
SHOT DEPTH 175 FT.
SLOPE -2.37 (BY LEAST SQUARES)
SHOT DEPTH 200 FT.
SLOPE -2.36 (BY LEAST SQUARES)
SHOT DEPTH 225 FT.
SLOPE -2.34 (BY LEAST SQUARES)
SHOT DEPTH 250 FT.
SLOPE -2.76 (BY LEAST SQUARES)
SHOT DEPTH 275 FT.
SLOPE -2.30 (BY LEAST SQUARES)
SHOT DEPTH 300 FT.
SLOPE -2.23 (BY LEAST SQUARES)
A₁=EARTH PARTICLE VELOCITY, CM/SEC
TRAVEL TIME, MILLISECONDS
GEOPHONE IN 8926 AT DEPTHS 834' AND 984'
SHOTS AT UNIFORM DEPTH IN SHOT HOLES N, A, B, O, C, P, D, E, F.

FIG. 18. Amplitude of earth-particle velocity plotted against travel time with shot depth held fixed—Limon, Colorado.

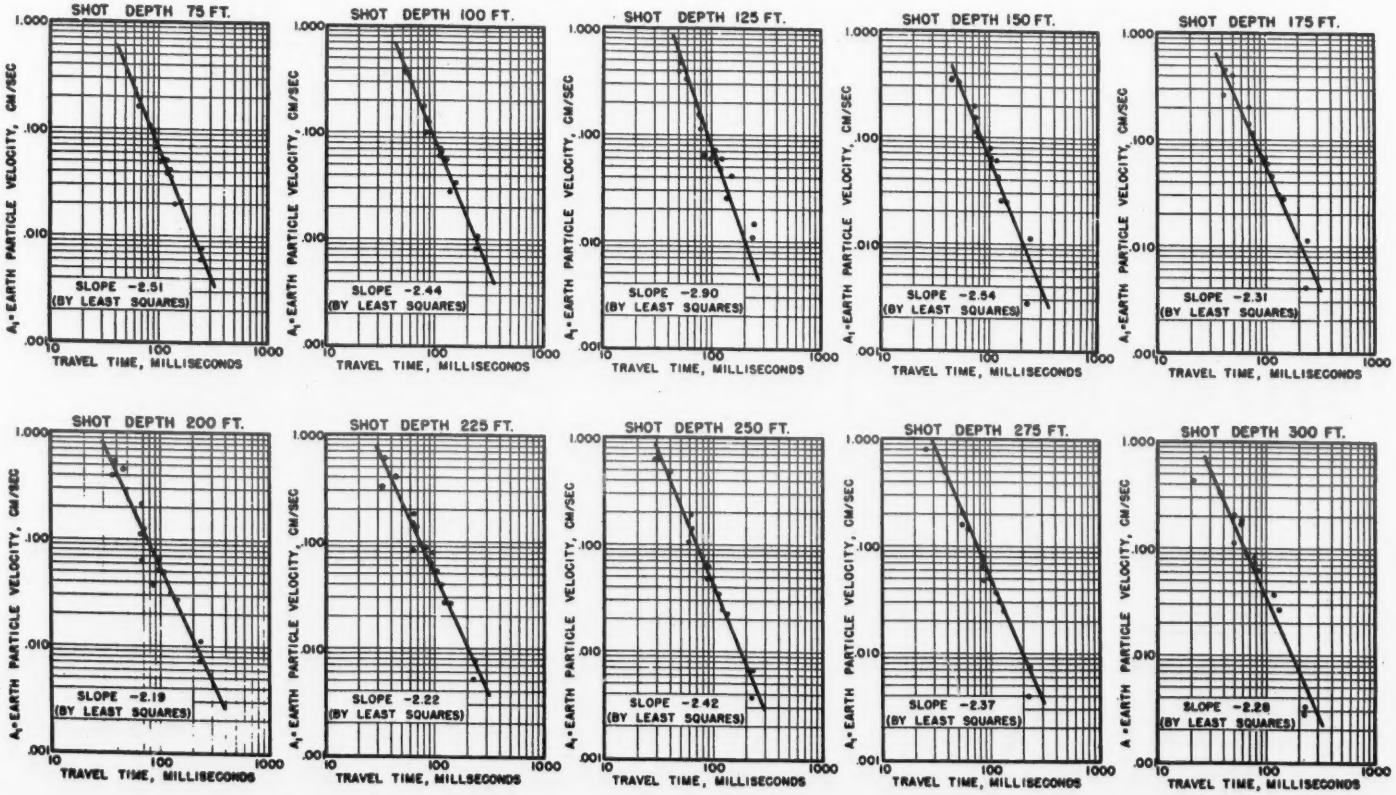
SHOT DEPTH 75 FT.
SLOPE -2.51 (BY LEAST SQUARES)
SHOT DEPTH 100 FT.
SLOPE -2.44 (BY LEAST SQUARES)
SHOT DEPTH 125 FT.
SLOPE -2.90 (BY LEAST SQUARES)
SHOT DEPTH 150 FT.
SLOPE -2.54 (BY LEAST SQUARES)
SHOT DEPTH 175 FT.
SLOPE -2.31 (BY LEAST SQUARES)
SHOT DEPTH 200 FT.
SLOPE -2.19 (BY LEAST SQUARES)
SHOT DEPTH 225 FT.
SLOPE -2.22 (BY LEAST SQUARES)
SHOT DEPTH 250 FT.
SLOPE -2.42 (BY LEAST SQUARES)
SHOT DEPTH 275 FT.
SLOPE -2.37 (BY LEAST SQUARES)
SHOT DEPTH 300 FT.
SLOPE -2.28 (BY LEAST SQUARES)
A1 = EARTH PARTICLE VELOCITY, CM/SEC
TRAVEL TIME, MILLISECONDS

FIG. 19. Amplitude of earth-particle velocity plotted against travel time with shot depth held fixed—Last Chance, Colorado.

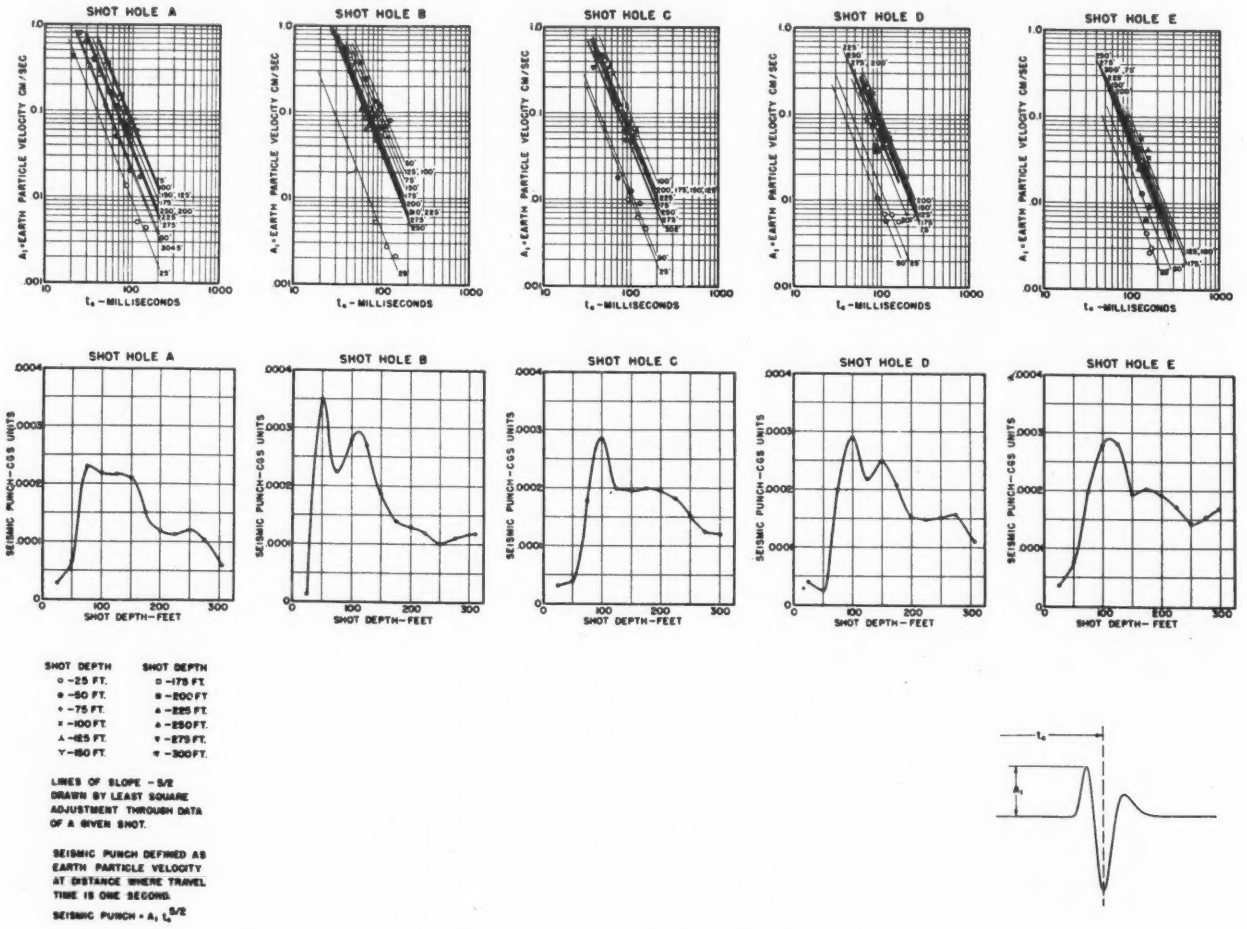

FIG. 20. The determination of seismic punch and its variation with depth of shot, Limon, Colorado.

will be seen that the pattern is quite similar for each of the shot holes, the seismic punch being very low for shallow shots, increasing to a maximum as the shot is deepened and then falling for the deeper shots.

On Figures 21 and 22 the average seismic punch for holes *A*, *B*, and *C* has been plotted as a function of the shot depth for Limon and Last Chance respectively. The values for shots deeper than 300 feet were obtained at the close of the program when the geophones were withdrawn and placed in redrills of the shot holes and shots were made in the deep hole.

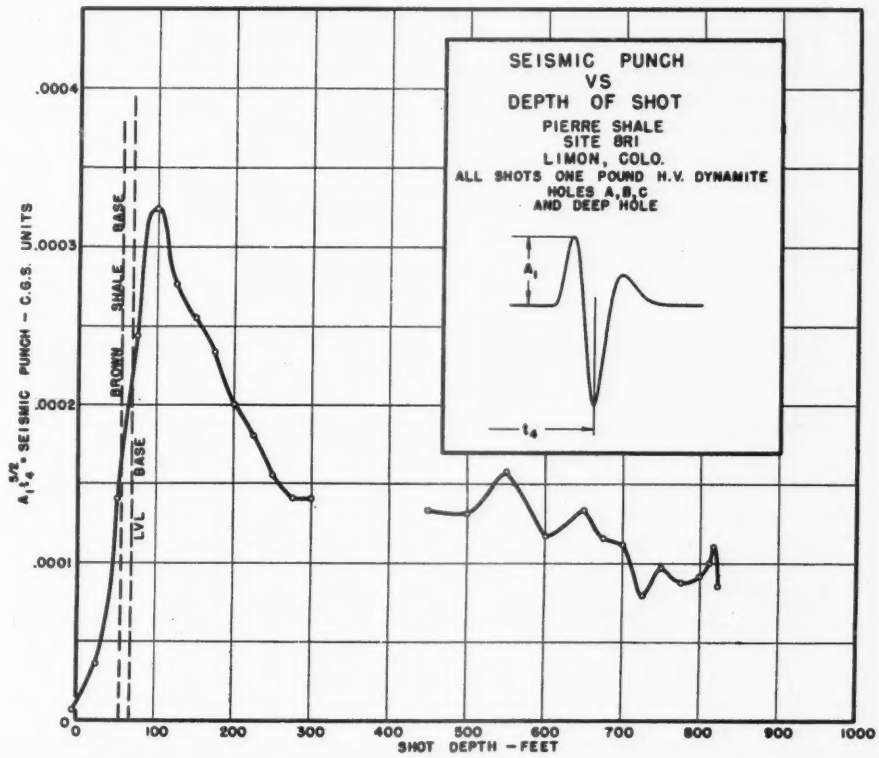

FIG. 21. Seismic punch vs. depth of shot, average for three holes, Limon, Colorado.

In Figure 23 the seismic punch has been contoured in section for the Limon area. There are a number of possible explanations for the variation of seismic punch with shot depth but a clear understanding of this effect will not be available without further studies. On Figure 24 there are drawn a set of graphs giving the earth-particle displacement, earth-particle velocity and earth-particle acceleration, the wavelet breadth and the distance traveled by the wavelet as functions of the travel time of the wavelet center. All are based on the predictions of the wavelet theory but are drawn for the propagation constants determined for the

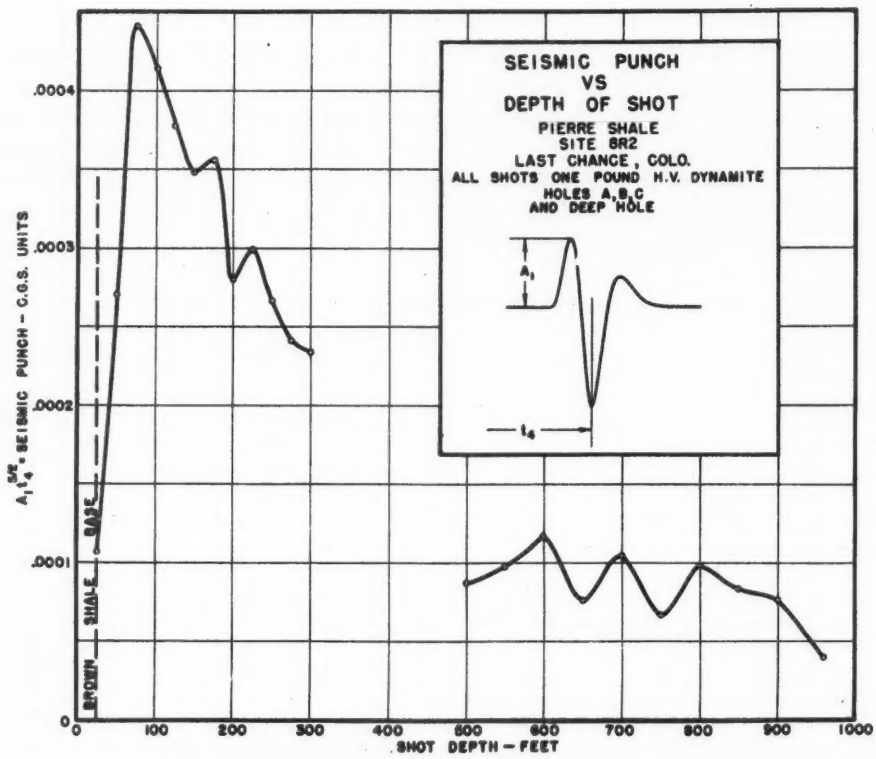

FIG. 22. Seismic punch vs. depth of shot, average for three holes, Last Chance, Colorado.

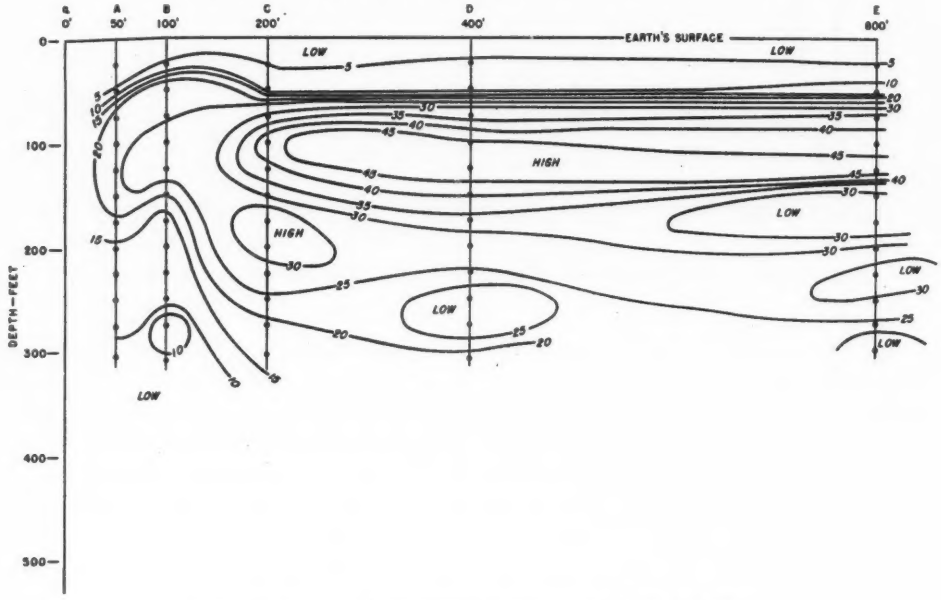

FIG. 23. Seismic punch contoured in section at Limon, Colorado.

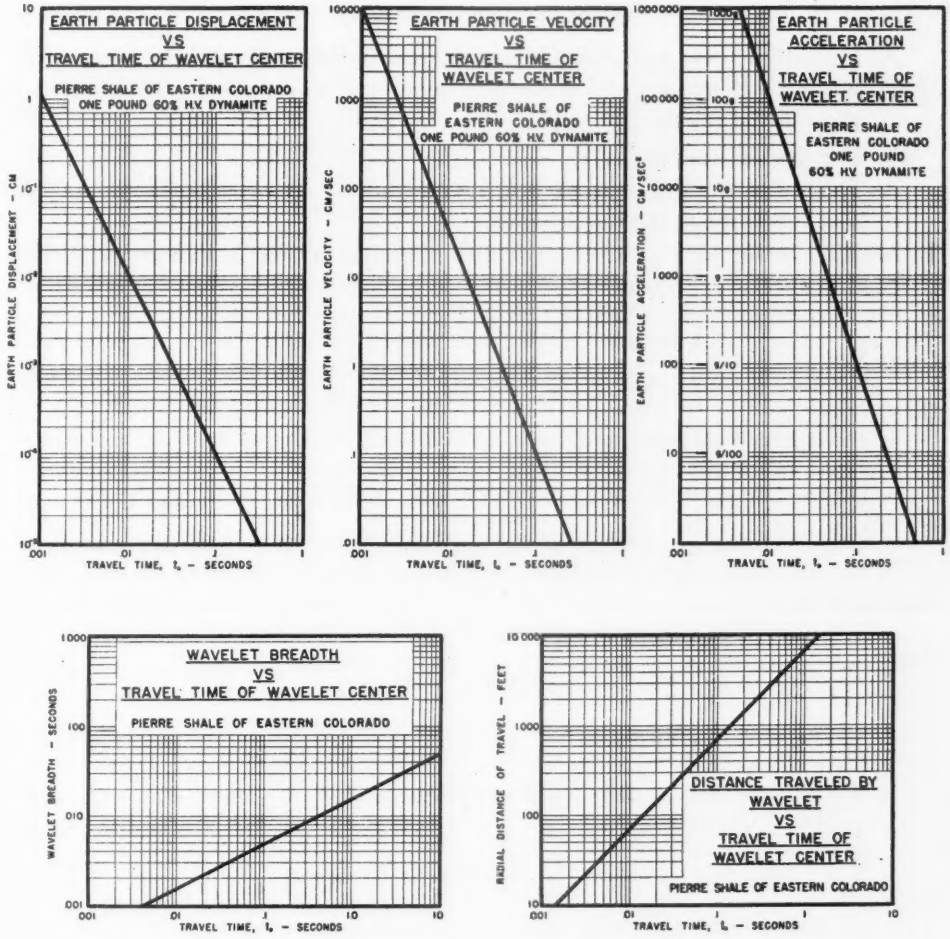

FIG. 24. Charts showing over-all seismic behavior of the Pierre shale.

Pierre shale by these experimental studies. The constants used in drawing these graphs are

$$c = 7{,}000 \text{ feet/second.}$$

$$\omega_0 = 50{,}000 \text{ radians/second.}$$

The quantity ω_0 is 2π times the transition frequency, f_0. Thus a representative value of the transition frequency for the shale at a depth of around 300 to 600 feet is 8,000 cycles per second. For a further discussion of this transition frequency reference may be made to the literature (Ricker 3, 4). This transition frequency marks a position in the frequency scale above which dispersion becomes important for sinusoidal waves and where the nature of the absorption changes.

SUMMARY AND CONCLUSION

As a result of these researches it may be concluded that, in shale, agreement of experiment with the wavelet theory has been good. These checks are relative to

a. The form of the disturbance.
b. The law of broadening.
c. The law of amplitude decay with travel time for the earth particle velocity.
d. The spectrum of the disturbance.

In addition to the above the effect of size of charge on the amplitude has been checked in special experiments and found to be close to the 5/6 power law.

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DISCUSSION

MR. D. T. GERMAIN-JONES (Anglo Iranian Oil Co., London, U.K.) commented upon the vagaries of the first kick as demonstrated in Figure 7, and he inquired whether the same effect is operating if the amplification is kept constant while the size of the charge is increased. He had observed a similar effect in long range refraction work, as sometimes the conventional first kick times recorded by the near geophone stations, with larger trace amplitudes, appear to be relatively too short; consequently the apparent velocity indicated by these first kicks would be too small. He felt that for the purpose of velocity determinations

first peaks give more reliable times than first kicks, provided of course that the first peaks are not complicated by later refractions.

In connection with the ellipsoidal form of the wave front shown in Figure 8, he asked whether the author had any comments on the question of a suitable overburden velocity to be used in refraction computations, as the horizontal velocity is too high whereas the vertical or cross-bedding velocity obtained from well shooting appears to be too low.

Referring to Figures 10 and 11 he wondered whether the velocity curves can actually be extrapolated down to values as low as 100 ft/sec. As a layer of such a low velocity at the earth's surface is probably immeasurably thin, he would have expected a cut-off of the curves at a velocity approximating that of sound in air.

MR. H. CLOSS (Geological Survey, Hanover, Germany) commented on the increase of wavelet breadth with travel time, and the corresponding decrease of apparent frequency. In a shot hole in Germany he had observed increasing frequency with increasing travel distance, but with increasing depth of the charge.* He drew the conclusion that the increase of frequency must be ascribed to a change in the originated spectrum of frequencies, which is perhaps a function of the depth of the charge; and he inquired if the author could confirm this opinion.

In a written comment MR. S. KAUFMAN (Shell Oil, Houston, Texas, U.S.A.) pointed to a discrepancy in the numerical values given by the author for the classical velocity of propagation ($c=7{,}000$ ft/sec.), the transition frequency $f_0=8{,}000$ c.p.s.) and the numerical distance ($R=25$). If these values are substituted in equation 5, the shooting distance r is found to be $3\frac{1}{2}$ feet, which is an unreasonably small value as the distances used in the experiment have ranged from 50 to 1,600 ft.

MR. C. H. DIX (Calif. Inst. of Techn., Pasadena, Calif., U.S.A.) commented in writing on the importance of the subject treated by the author. Then he pointed out that in his opinion failure of the medium to be perfectly elastic is not the only cause of wavelet shape variation. Heterogeneity contributes to this effect through scattering and path disturbances; imperfectly plane reflectors also lengthen wavelets. Only specially selected transformations would shorten a wavelet, while random transformations generally lengthen it.

MR. T. KREY (Seismos, Hannover, Germany) commented on the residual obtained by subtracting the ideal wavelet form from the observed one. If we are indeed dealing with bubble pulses, then the time difference of $3\frac{1}{2}$ milliseconds between the center of the ideal wavelet and the center of the succeeding residual wave must be independent of the travel time. However, for very large distances the two waves must practically coincide, because the interval of $3\frac{1}{2}$ milliseconds will be small compared with the breadth of the wavelets, on account of the law of broadening. Consequently, for large distances there should not be any meas-

* Vide Closs, Hans, "Applied Geophysics in West Germany during the Last Five Years," Proceedings Third World Petroleum Congress, Leiden 1951, Section I, p. 564.

urable difference between the observed motion and the ideal wavelet form. The speaker considered this point to be worth investigating.

MR. N. D. SMITH (Shell Oil, Houston, Texas, U.S.A.) pointed out that the importance of the paper lies in the demonstration that the Stokes' equation, and the assumption of a simple shot pulse containing all frequencies, predict the qualitative changes in the seismic signal as a function of the travel distance. He felt that the initial disturbance produced by an explosion is certainly more complicated than that assumed by the author, and that such differences in frequency distribution may account for the deviations observed between theory and experiment in the later stages of the wavelet, and for the rather wide variations of the cut-off frequency with the location of the shot.

The author's seismic punch and its variation as a function of the position of the shot are well known in a qualitative way to every field seismologist, but the quantitative approach and the detailed study of figure 23 are new and very interesting; the speaker considered that additional studies would be of great practical importance.

Speaking on behalf of the author, Mr. T. V. MOORE (Standard Oil Development Co., New York, U.S.A.) agreed with Mr. Dix that there are many factors that can result in broadening of wavelets besides the theory of friction, which is taken into account by the Stokes' equation. However, the experiments have indicated that this theory goes a long way toward explaining many of the seismic phenomena.

He felt that an experimental study along the lines suggested by Mr. Krey would be handicapped by the complex nature of a seismogram which records energy that has travelled a long distance through the earth.

In a written reply to the various comments the author, MR. RICKER, points out that according to theory the conventional first kick should advance through any agency that increses its trace amplitude, but he has not made an experimental study of the effect of charge size on the advance; he agrees with Mr. Germain-Jones' preference for first peak times.

Relative to the 100 ft/sec. velocity near the earth's surface, he revealed that in addition to the theoretical arguments presented in the paper this estimated value is based on special experiments. Geophones were set at intervals of one foot, and records were taken of the explosion of a blasting cap, which was covered with a sound-deadening cover to diminish the air wave. Velocities of 500 ft/sec. were observed quite frequently, and in one instance a velocity as low as 300 ft/sec. has been recorded. These very low velocities must lie within the first few inches of the earth's surface.

In reply to Mr. Closs the author reports that in observations with a deeply placed geophone he has indeed observed a very great change in wavelet breadth with charge depth. When the depth of the shot is varied from 300 to 100 ft., the wavelet breadth may change from .004 to .006 second. This effect is further enhanced as the shot is placed up in the highly absorbent low velocity zone, the

breadth increasing to .009 sec. for a shot depth of 50 ft, and becoming much broader for still shallower shots. The author's measure of these changes in the absorbing properties of the rocks at various depths is through what he calls the transition frequency, which has been discussed in his earlier papers. For sinusoidal waves decaying exponentially as

$$A = A_0 \epsilon^{-\alpha x} \cos 2\pi f \left(t - \frac{x}{c} \right)$$

the absorption coefficient α is given by

$$x = \frac{\pi f^2}{c f_0}$$

for low frequencies, c being the wave velocity, f the wave frequency, and f_0 the transition frequency of the earth. This transition frequency may be determined experimentally by observations of wavelet breadths; the procedure is to plot b^2 against the travel time t_4, draw a smooth curve through the data points and then draw tangents to the resulting curve. One has then:

$$f_0 = \frac{6}{\pi} \cdot \frac{\Delta t_4}{\Delta(b^2)} .$$

For depths of 300, 200, 100 and 50 feet the transition frequency is found to be 8,000, 5,000, 2,000 and 300 cycles/sec. respectively; very low values are reached at shallower depths.

The discrepancy mentioned by Mr. Kaufmann must according to the author be explained by the fact that the Pierre shale is not homogeneous. He points out that the wavelet is shaped in the near vicinity of the shot and moves downward into a region of higher and higher transition frequency. The peak frequency of the wavelet spectrum is around 200 cycles, which is low compared with the transition frequency of the earth below it. Since a change in form of the wavelet is to be effected only through dispersion (a change in breadth is not a change in form), it may be seen that this dispersion is too small to permit the parameter R of the form to increase appreciably. If v is the velocity of waves of frequency f, f_0 the transition frequency of the medium, and c the wave velocity approached as f becomes vanishingly small, there exists for low frequencies the approximate relation

$$\frac{v}{c} = 1 + \frac{3}{8} \cdot \frac{f^2}{f_0^2}$$

which for $f = 200$ and $f_0 = 8{,}000$ gives $v/c = 1.00024$. Thus the dispersion is quite small and evidently does not allow the parameter R of the wavelet form to keep pace with the numerical distance as determined for a homogeneous medium by equation 5 of the paper. This observation is one of the interesting things which

point to the desirability of making further studies in the zone immediately surrounding the shot.

In commenting on the remarks made by Mr. Dix the author points out that although there are many matters yet to be considered it was his idea to first determine the basic form (or series of forms) assumed by a seismic disturbance in an ideal homogeneous absorbent earth. This form is offered as a better basis for further studies than continuous sinusoidal waves. The seismic wavelet, as the author defines it, is an ideal mathematical entity and not subject to the vagaries of passage through a heterogenous medium; in the author's opinion Dix is actually thinking of modifications in the wavelet complex due to changes in the spacings and relative amplitudes of the component wavelets.

Referring to some of the comments made by Messrs. Smith and Krey, the author expresses his agreement with Mr. Krey's conception of the processes involved in the propagation of a seismic wave. He adds that in addition to the bubble pulses also the effects of other phenomena, such as finite strains immediately surrounding the shot and the variation of pressure in the shot cavity as a function of time, are being ironed out at greater distances. Regardless of the shot characteristics the earth finally takes over and controls the shaping of the disturbance.

GULF COAST SURFACE WAVES*

LYNN G. HOWELL,† E. F. NEUENSCHWANDER,† AND A. L. PIERSON III†

ABSTRACT

Surface wave recordings were made with the following: a three-component velocity seismometer, a long-period displacement seismometer, six dynamic seismometers, an air-actuated condenser microphone, and a vertical strain seismometer. Wave trains were recorded similar to those obtained by B. F. Howell in California. We have divided the surface waves into two trains instead of three. The early train seems to have properties of the M-2 wave of Sezawa; the late train seems to be a Rayleigh wave. An air-coupled wave is shown to be associated with the M-2 wave. In the group velocity dispersion curve of the Rayleigh wave, the short-period branch was found as predicted by theory as well as the usually observed long-period branch. By making certain assumptions, the thickness of the top layer appears to be about 50 feet according to the theoretical curves of Kanai.

Studies have been made of seismic surface waves generated by dynamite explosions in a small area near the Humble Friendswood Experimental Station. The area is roughly 15 miles Southeast of Houston. This work is of interest both as to the instrumentation used and the results obtained.

INSTRUMENTATION

Various types of seismometers were used. Ground velocity recordings were made with a three-component seismometer composed of variable reluctance units. The vertical unit has a natural frequency of abot 2.5 cps while the horizontal units have a natural frequency of about 1.5 cps. Oil damping is used and is roughly one-half critical. The outputs of these units are fed into preamplifiers which are condenser-coupled to DC amplifiers. The over-all amplifiers are flat in the lower frequency range to about 2 cps, the upper limit being set by the 100-cycle galvanometers.

Vertical velocity recordings were made with a spread of six dynamic pickups, having a natural frequency of about 7 cps. The apparent natural frequency rises to about 11 cps when these units are couplied to the input transformers of the condenser-coupled amplifiers.

Vertical displacement recordings were made with a converted gravity meter having a Truman suspension with a natural period of roughly 3 seconds. The damping produced by a vane moving in a magnetic field amounts to about 0.4 critical. The amplification is DC throughout. Figure 1 shows a schematic drawing of the seismometer, including the light beam and photo-cell arrangement for detecting displacement.

Air pressure records were made with a GR 3C Sound Ranging Set, built

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† Humble Oil & Refining Company, Houston, Texas.

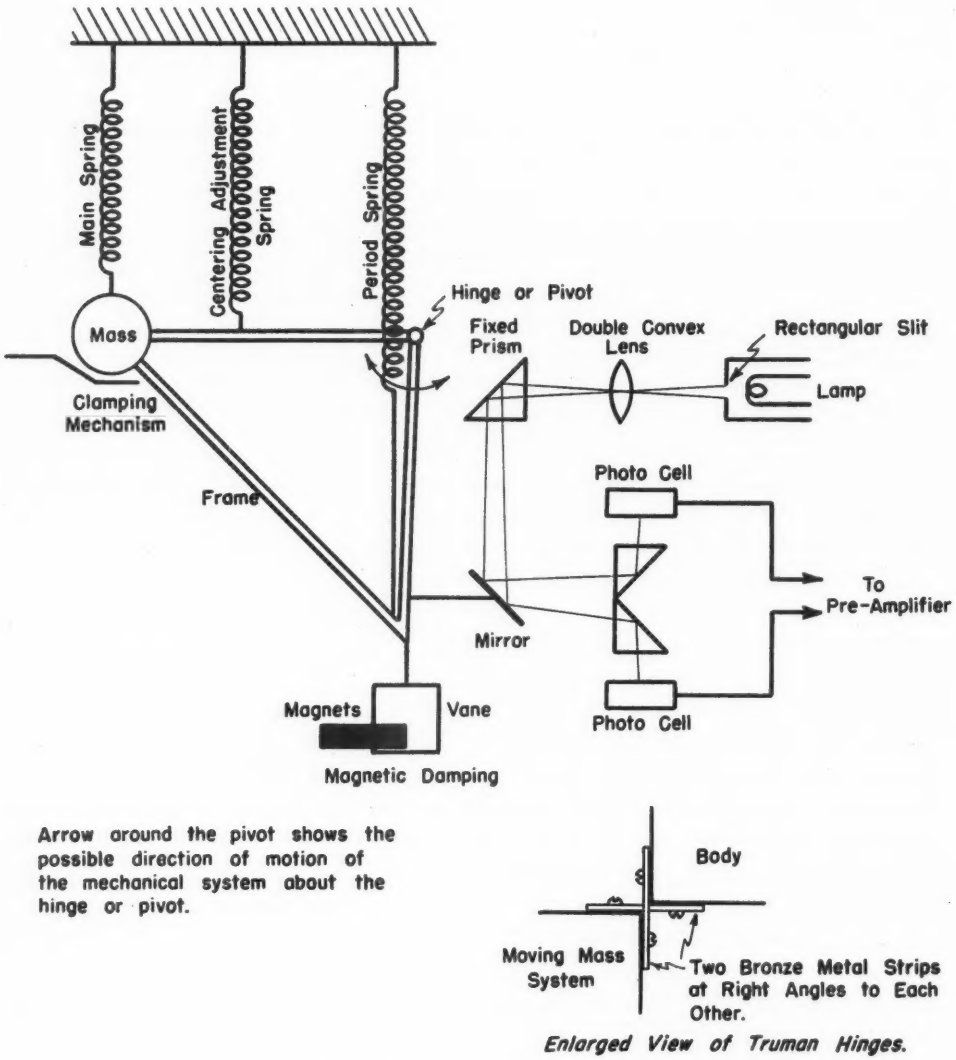

FIG. 1. Displacement seismometer.

for the Armed Services. This unit consists of a condenser microphone inside a Helmholtz resonator which is coupled to another Helmholtz resonator, the latter being in turn coupled to the air. This resonator arrangement was built to give a low-pass acoustic filter, cutting off at about 25 cps. We altered the volume of one of the resonators slightly by removing the amplifier. The microphone is coupled through a condenser to a DC amplifier.

Vertical strain records were made with a seismometer shown in Figure 2.

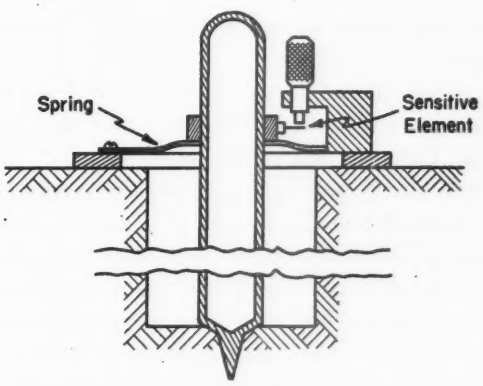

FIG. 2. Vertical strain seismometer.

This gage is similar to the Benioff[1] strain seismometer used for many years in earthquake seismology. However, it differs in two essentials: (1) it measures vertical instead of horizontal strain and (2) it measures displacement differential instead of the time derivative of the displacement differential. In the figure,

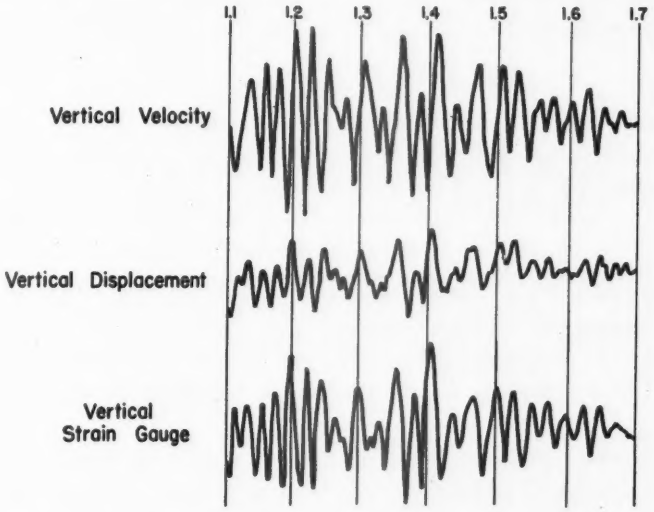

FIG. 3. Comparison of velocity, strain, and displacement traces.

the vertical dural tube transmits the motion of the ground at the bottom of a 7 foot hole to the surface. Here, the differential movement between the bottom of the hole and the surface is registered by the sensitive element which is itself a strain gage, adapted from a phonograph pickup. The tube is centered in the

[1] H. Benioff, *Bulletin of the Seismological Society of America*, Vol. 25 (1935), p. 283.

hole by means of the leaf spring shown in the figure. The amplification for this gage is DC throughout.

The strain gage should record a wave form proportional to the vertical velocity trace for a compressional wave traveling in the vertical direction. This is so since, in this case, the time derivative is proportional to the vertical space derivative of the wave function. Figure 3 shows the striking similarity between the strain and the vertical velocity traces of P waves recorded at a location 3,750 ft from the shot which consisted of $2\frac{1}{2}$ pounds of dynamite fired in a 45 ft hole. This similarity occurs even though the seismometers are located at a free surface; in general, one does not find such close correlation. As would be expected, the displacement trace shown also bears some resemblance to these traces; in this case, the displacement trace is turned over in phase from the usual recording.

As to the vertical component of surface waves, the strain gage should give a recording proportional to displacement. Here, the vertical displacement may be written

$$w = F(z)f(x - ct) \tag{1}$$

where z is the vertical coordinate, x is the horizontal coordinate in the direction of wave travel, c is the wave velocity, and t is the time.

Thus, the strain

$$\frac{\partial w}{\partial z} = F'(z)f(x - ct) \tag{2}$$

is still proportional to $f(x-ct)$ and not $f'(x-ct)$ as is the vertical velocity. Examples of this will be seen later.

SURFACE WAVES

This study of surface waves is restricted to one small area where the records are, at least in part, amenable to analysis. Thus, the area is not to be regarded as altogether typical. Representative of the countryside, however, are the surface, a black clay, and a shallow water table which occurs at a depth of the order of 15 ft.

Figure 4 shows a recording made at 2,800 ft. from a $2\frac{1}{2}$ pound charge of dynamite shot at a depth of 20 ft. Four traces are presented: vertical velocity, radial velocity, vertical displacement, and vertical strain. The transverse horizontal velocity trace is not considered to be of sufficient interest for reproduction. In fact, at distances under 2,800 ft its relative amplitude becomes fairly small. For the traces shown, a positive or upward value of the vertical velocity trace represents an upward velocity of the ground, a positive value of the radial velocity trace represents a velocity away from the shot, a positive value of the displacement trace represents an upward displacement of the ground, and finally, a positive value of the strain trace represents a compression of the ground.

One interesting point concerning this record is that the strain gage relative to

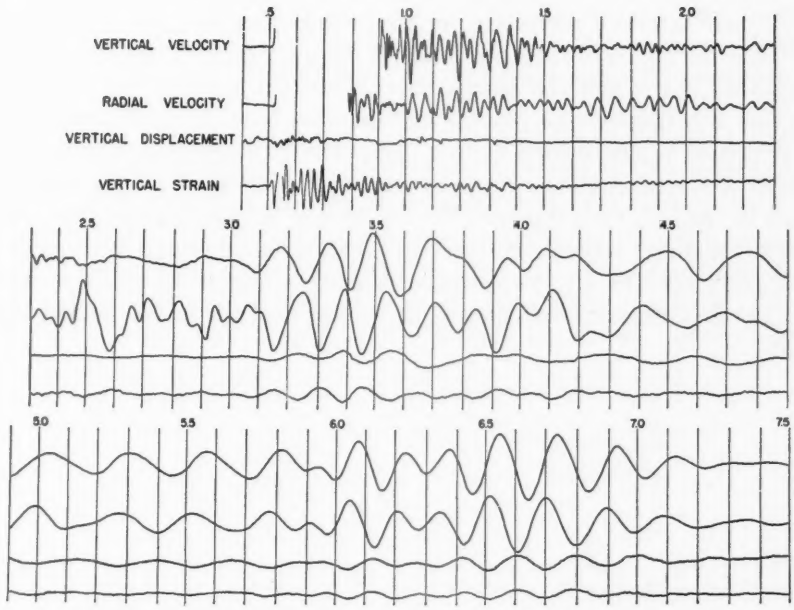

FIG. 4. Recording at 2,800 ft. with 2½ pounds dynamite shot at depth of 20 feet.

the vertical displacement seismometer is much more sensitive to the compressional waves in the early part of the record than to the surface waves which begin at about 2.5 seconds. This is to be expected with the surface waves since the ground moves up and down in phase and with the same order of amplitude along a vertical line. In other words, in equation (1) (F(z) changes slowly with z. Hence, $F'(z)$ is small and thus the strain is relatively small. This suggests a method of reducing "ground roll" in reflection methods, although it is possibly not the most convenient one.

We may divide the surface waves beginning at 2.5 seconds into two trains.

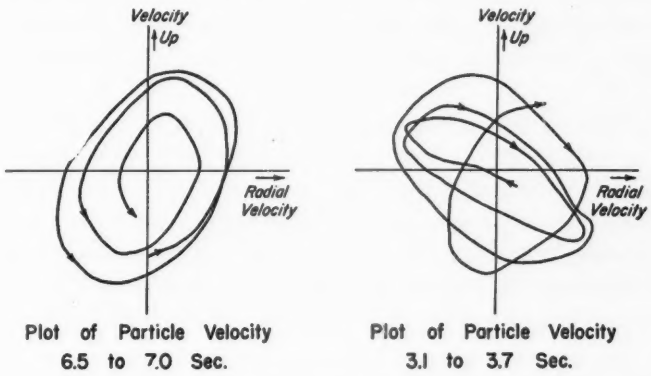

FIG. 5. Ground particle velocity patterns.

The first train attains a maximum amplitude in the region 3.1 to 3.7 seconds and the other in the region 6.5 to 7.0 seconds. A distinguishing difference in these two trains is that in the first the ground particle motion is direct and in the second the motion is retrograde; i.e., in the first case, the vertical trace leads the radial trace in phase; in the second case, it lags. The retrograde motion is of course typical of a Rayleigh wave. Figure 5 shows qualitatively the particle velocity patterns in the two time intervals shown. As can be seen, the particle describes ellipses in the direct sense in the interval 3.1 to 3.7 seconds and in the retrograde sense in the interval 6.5 to 7.0 seconds. In neither case is the phase relationship 90°; in the first instance the ellipses tilt backward while in the second they tilt forward.

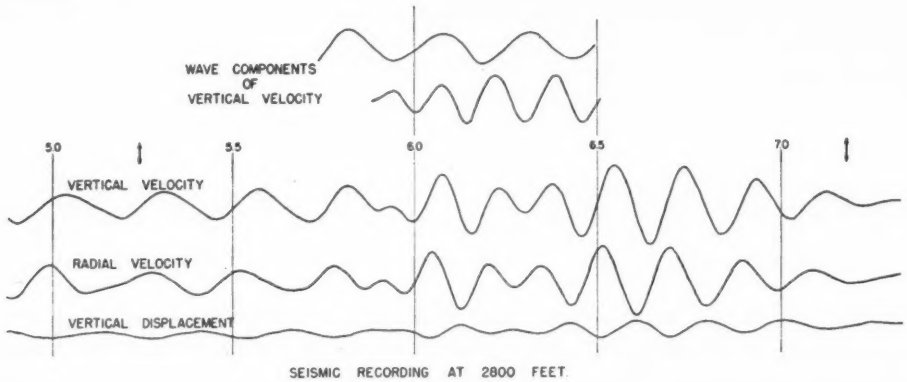

FIG. 6. Rayleigh wave train.

It is quite interesting that very similar wave trains to these were observed by B. F. Howell[2] in the neighborhood of Los Angeles. He divided the trace into three trains instead of two and called them *C*, *H*, and *R*. These waves cover velocity ranges similar to ours. His *C* train is the first arriving wave which is largely radial in movement. We prefer to regard this as part of the succeeding wave train. The particle velocity patterns for his *H* and *R* waves ressemble our patterns in Figure 4 both in direction of motion and even in direction of tilt of the ellipses.

The wave train at the end of the record is readily identifiable as a Rayleigh wave, since as previously noted the particle motion is retrograde. In addition, it will be seen in Figure 4 that the strain trace is in phase with the displacement trace and not the velocity trace as as discussed earlier. Since the ground is in compression as it rises, it is indicated that the vertical component of the wave increases with depth at the surface. This is in agreement with the usual theory of Rayleigh waves,[3] showing a rise in amplitude of the vertical component with

[2] B. F. Howell, *Bulletin of the Seismological Society of America*, Vol. 39 (1949), p. 285.
[3] H. Jeffreys, *The Earth*, The MacMillan Company (1929), p. 91.

depth, followed by a decrease. The actual ground movements (total amplitude) at about 6.7 seconds are as follows: a ground vertical displacement of 11×10^{-5} inches and a differential displacement for the seven feet of ground column of 0.8×10^{-5} inches.

A dispersion analysis of the Rayleigh wave train has yielded interesting results. Group velocity data were obtained using the vertical velocity trace between the two arrows shown in Figure 6, which shows the latter part of the record of Figure 3. It will be noticed that the train begins with a long period at some time before 5.3 seconds and continues with fairly constant amplitude to about 5.8 seconds when a shorter period train begins which beats with this initial wave. The two components have been separated in the two upper traces. The

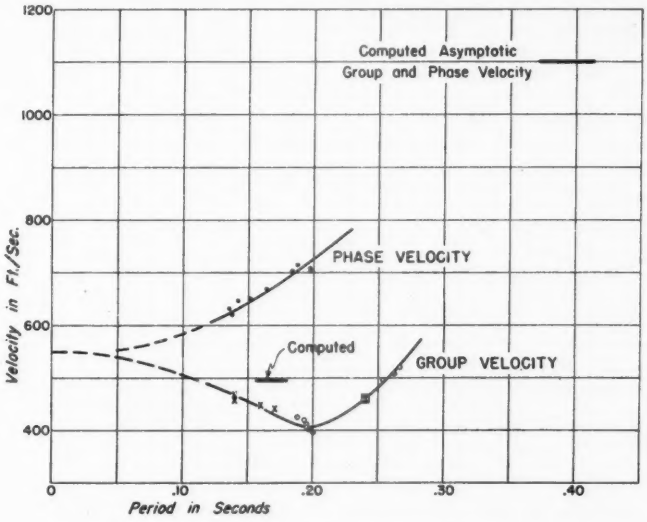

FIG. 7. Rayleigh wave dispersion curves.

short period wave builds up to an amplitude about equal to that of the long period trace. The period of the initial wave decreases and the period of the second train increases until at about 6.5 seconds the two begin to unite in phase and period to form the large amplitude train. This large amplitude wave, which is one of the chief components of ground roll, has been called the Airy phase by Pekeris[4] and Ewing in their work in sound propagation in thin layers of water.

Figure 7 shows the dispersion curves for the Rayleigh waves. The data for the group velocity curve were obtained from the traces of Figure 6. The periods represented by the circles were obtained from the zero crossings of the vertical velocity trace. The crosses were obtained from the resolved curves at the top of Figure 6. The cross inside a square was obtained from an average of three cycles.

[4] Ewing, Worzel, Pekeris, "*Propagation of Sound in the Ocean*," *The Geological Society of America* Memoir 27 (October 15, 1948).

This curve is of particular importance since in general the short period branch to the left of the Airy phase at a period of about 0.20 seconds has not been previously observed on land[5] with dynamite shots.

The phase velocity curve was obtained from the 6 traces of the dynamic seismometers in Figure 8. Here, only the short periods were recorded due to the lack of response of the seismometers to long periods. Times of peaks were tabulated. The group velocity computed from the phase velocity curve is shown by the solid line marked "computed." The computed velocity is higher than the measured values of group velocity. However, it must be remembered that the

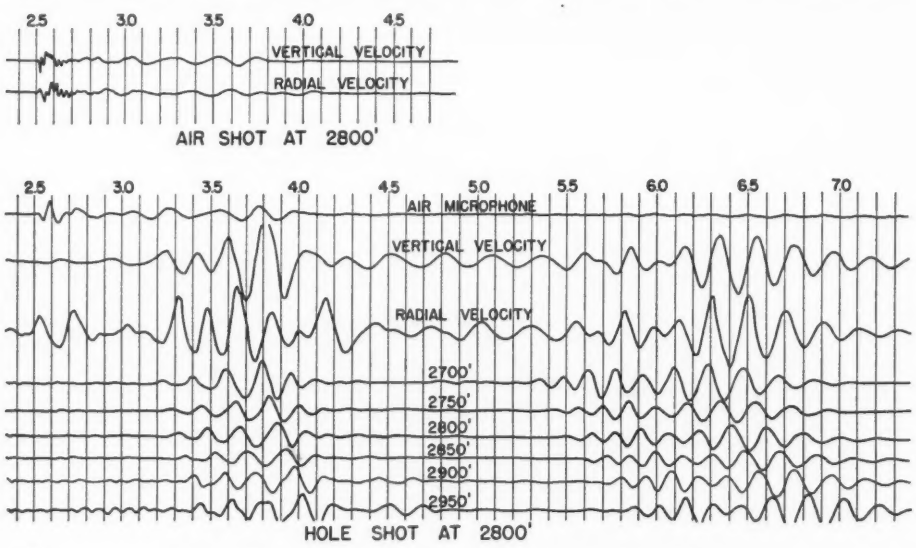

FIG. 8. Recordings of air coupled wave with air shot and hole shot.

phase velocity is measured locally over the spread of the seismometers while the group velocity is averaged over the whole interval between the shot hole and the seismometer. The group velocity is a few percent higher for the vertical velocity trace shown in Figure 8 as compared to Figure 6; these records were made about 7 months apart.

The short period asymptotic velocity is sketched in at 550 feet per second. This is the average Rayleigh velocity of the top surface layer. A further analysis of this layer may be made using the theoretical curves of Kanai,[6] whereby a value of the thickness of the layer may be obtained. We make the following assumptions: (1) the density is the same in the top layer and the medium beneath, (2) the ratio λ_1/λ_2 of the Lame's elastic constants in the top layer and the medium underneath is equal to the ratio μ_1/μ_2 of the shear moduli in the two media, and (3) a ratio of

[5] F. Press and M. Ewing, *Geophysics*, XVI, 16 (1951), p. 416.

[6] K. Kanai, *Bulletin of the Earthquake Research Institute*, Tokyo University, Vol. 29 (1951), p. 49.

0.92 is taken for the Rayleigh velocity relative to the shear velocity. Thus, we get a value of 600 feet per second for the shear velocity in the top layer. The minimum group velocity from the curve is 405 feet per second. The value of μ_2/μ_1 corresponding to the ratio of the two velocities, 405/600, is obtained from Kanai's curve in round numbers equal to 3.5. The phase velocity for the period of 0.20 seconds corresponding to the minimum group velocity is 730 feet per second. The ratio of the two velocities 730/600 leads to a value of μ_2/μ_1 from another curve of Kanai amounting to 4.4. Thus we get an average μ_2/μ_1 of 4. Since the Rayleigh waves in the two media are assumed to have velocities proportional

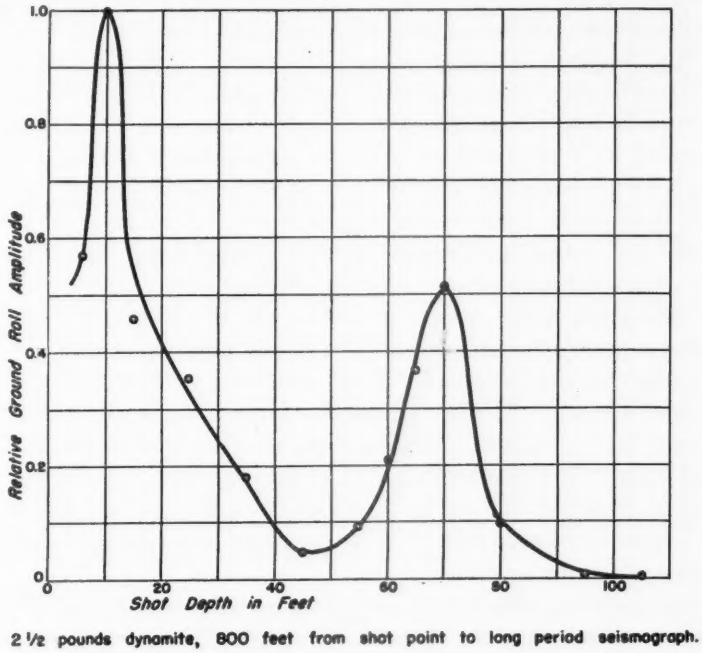

FIG. 9. Amplitude of Rayleigh wave as a function of shot depth.

to the shear waves, the Rayleigh wave velocity in the lower medium comes out to be $\sqrt{\mu_2/\mu_1}$ or twice the Rayleigh wave velocity in the top layer. This value of 1,100 feet per second is shown as the asymptotic velocity in Figure 7. With the ratio μ_2/μ_1 of 4, still another curve of Kanai, relating μ_2/μ_1 to L/H, gives a value of L/H equal to 3; here, H is the thickness of the top layer and L is the wave length for a period of 0.20 seconds at the minimum group velocity. Since L is about 150 feet, the thickness of the layer comes out to be about 50 feet.

In Figure 9 is shown the amplitude of the Rayleigh wave (Airy phase) as a function of shot depth at a distance of 800 feet from a shot hole. It is interesting to note that the curve passes through a minimum at a depth of about 50 feet, the calculated thickness of the top layer. This curve is quite similar to that sometimes

obtained in microwave transmission[7] through an overwater duct when a maximum signal is received with the transmitter inside the duct, a minimum with the transmitter near the top and a second smaller maximum with the transmitter above the duct.

The earlier wave train in Figure 4 seems to satisfy some of the criteria of an M-2 wave, the theory of which was developed by Sezawa and Kanai.[8] In the first place, the particle motion is direct as is demanded by theory. Also, the vertical motion falls off with depth at the surface.[9] This is shown by the 180° out-of-phase relationship between the vertical displacement and the strain traces; hence, a compression is obtained when the ground moves down and the amplitude decreases with depth. The total amplitudes measured at about 3.4 seconds are as follows: ground vertical displacement, 9×10^{-5} inches; and differential displacement for the seven foot column, 1.3×10^{-5} inches. As Kanai[10] has shown, the group velocity curves in some cases may go through maxima as well as minima, the number varying with the elastic relationship. Thus, more than two frequencies may appear with the same group velocity or in other words, at the same place on the trace. As can be seen in our record, the frequency pattern is quite complicated. Again, Kanai[9] has shown that in some cases the radial component may be much larger than the vertical for particular frequencies. Hence, we are inclined to include the first large radial motion as part of the M-2 wave train extending on through the 3.1 and 3.7 second region. It may be mentioned that although the first large motion on the radial trace comes in with a group velocity close to the velocity of sound in air, at longer distances a large radial early arrival comes in with a higher veolcity. Suggested explanations are: deeper penetration is attained at longer distances, or, a different portion of the spectrum is arriving.

Haskell[11] has pointed out that B. F. Howell's H-wave occurs in the neighborhood of the velocity of sound in air and that there is a strong possibility of air coupling with the surface wave.

In our case, we have recorded ground waves with an air shot and air waves with a ground shot as was done by Press and Ewing[12] in their work on air coupled Rayleigh waves. The traces obtained are shown in Figure 8, there being a negative time correction of 0.03 seconds for the hole shot. The top record was made from a dynamite shot of 5 pounds at a height of 3 ft in the air. Only the significant part of the record is shown since for the most part the traces were dead, even the early *P* arrivals being very weak. The lower record was made from $2\frac{1}{2}$ pounds of dynamite shot at a depth of 24 feet. The air microphone was placed in an open hole to avoid wind noises and was isolated from the ground with foam

[7] Katzin, Bauchman, and Binnian, *Proceedings of the IRE*, Vol. 35 (1947), p. 891.
[8] K. Sezawa and K. Kanai, *Bulletin Earthquake Research Inst.*, Tokyo U., Vol. 13 (1935), p. 471.
[9] K. Kanai, *Bulletin of the Earthquake Research Institute*, Tokyo U., Vol. 29 (1951), p. 39.
[10] See reference 6.
[11] N. A. Haskell, *Bulletin of the Seismological Society of America*, Vol. 41, (1951), p. 295.
[12] See reference 5.

rubber. A positive displacement of the microphone trace indicates a compression of the air.

In both cases, the ground seismometers with the air shot and the microphone with the hole shot, an air coupled wave immediately following the arrival of the sound wave is recorded. There is a strong contrast in amplitude for the air pressure recording of the M-2 wave and of the Rayleigh wave. In fact, the air wave is just discernible for the Airy phase of the Rayleigh wave.

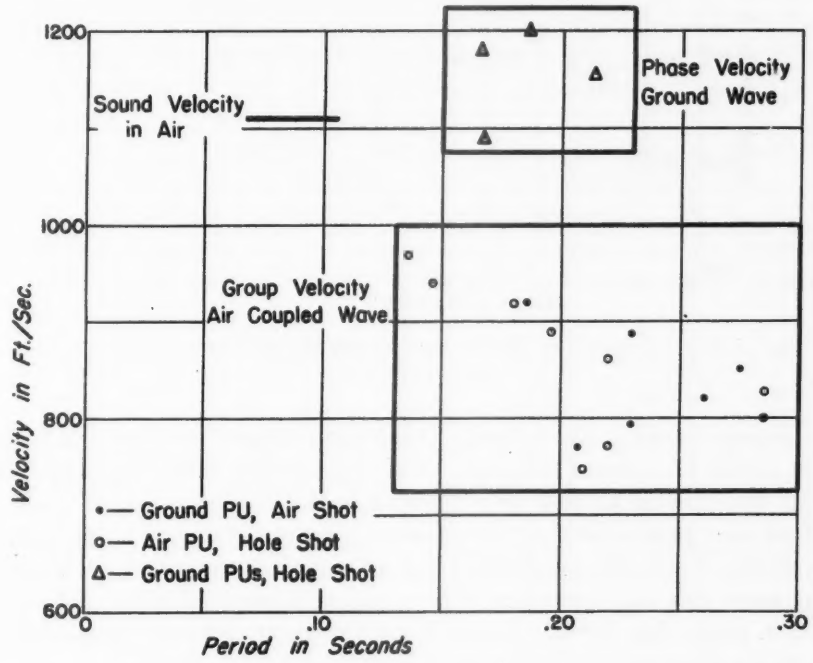

FIG. 10. Plot showing dispersion of phase velocities of ground wave and group velocities of air coupled wave.

Figure 10 shows a plot of group velocities of the air-coupled wave and of phase velocities of the ground wave as related to the period of the waves. The air coupled wave points were obtained using both peaks and valleys on the microphone trace and on the vertical velocity trace for the air shot. The phase velocity points were obtained using the peaks on traces of the six dynamic pick-ups.

Again the phase velocity curve is limited by the lack of response of the seismometers to long period waves. However, it will be noted that the points do fall in the neighborhood of the velocity of sound in air. An unusual feature of the group velocity points is the large spread in periods of the air coupled wave. This

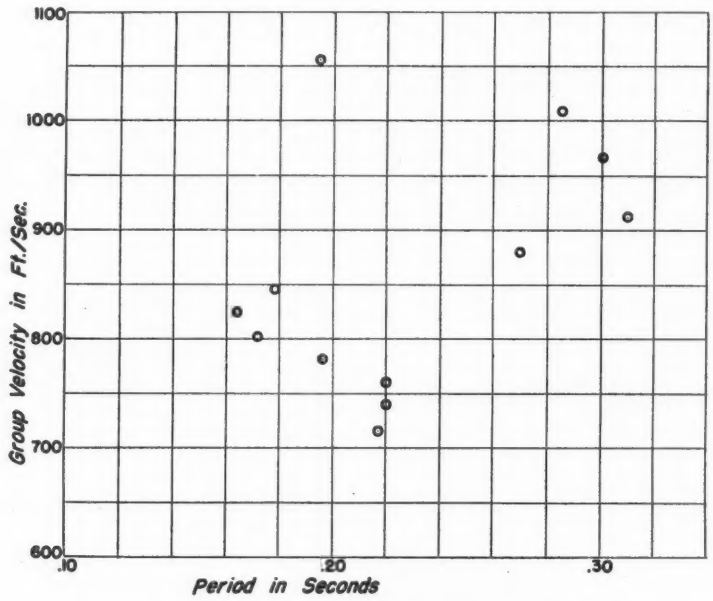

FIG. 11. Plot showing dispersion of group velocities of ground wave occurring between 2.5 and 4.0 seconds.

is in contrast to the work of Press, Ewing[13] and Dobrin[14] who reported a single period in the air-coupled Rayleigh wave, this period being the period of the ground wave having a phase velocity equal to the velocity of sound in air.

If we were to assume that the phase velocity of the ground wave is equal to the velocity of sound in air for the range of periods in our air coupled wave and furthermore that only one mode of propagation is involved, we would come out with the result that for the ground wave the group velocity equals the phase velocity for these periods. This comes from the relation,

$$U = c + K\frac{dc}{dK} \tag{3}$$

where U is the group velocity, c is the phase velocity, and K is $2\pi/L$, L being the wave length. Thus for the case $dc/dK = 0$, $U = c$. This is obviously not so from our record where the group velocities are less than the phase velocities as will be seen later. In fact, there is evidence that air waves are generated over a broad range of phase velocities of ground waves. This may be seen from the fact that the Airy phase of the Rayleigh wave, which has a phase velocity in the ground of only 700 feet per second, appears with a small amplitude as an air wave on the

[13] See reference 5.

[14] Dobrin, Simon, and Lawrence, *Transactions of the American Geophysical Union*, Vol. 32, (1951), p. 822.

microphone trace in Figure 8. In passing, it may be mentioned that in this area very little *P*-wave energy is transferred from the air to the ground when a charge is fired in the air.

Figure 11 shows a plot of the group velocities as a function of period for the ground wave between 2.5 and 4.0 seconds. Times of both peaks and valleys were used from the vertical velocity trace. The picture is certainly not a simple one. The *M*-2 wave should have a cut-off frequency at the low end.[15] This would be difficult to determine from our data. It appears that we need more data over a larger frequency range for both the phase velocities and the group velocities. As previously mentioned, the points do show that the group velocity is less than the phase velocity (Fig. 10) for the limited range of periods. Also the three points with lowest group velocity are associated with a high amplitude much in the manner of the Airy phase of the Rayleigh wave.

In conclusion, the authors wish to thank Dr. Maurice Ewing for a very helpful talk, and Dr. P. Byerly for suggesting the possible application of the Sezawa theory to our work. We also wish to acknowledge the work of Mr. W. A. Youngblood in the development of the strain gage. The authors wish to express their appreciation to Humble Oil & Refining Company for permission to publish this material.

[15] See reference 9.

VELOCITY MEASUREMENTS IN NEAR-SURFACE FORMATIONS*

J. E. WHITE† AND R. L. SENGBUSH†

ABSTRACT

Procedures are described for measuring various seismic velocities at shallow depths in the earth, and examples of the resulting logs are presented. Velocities in Austin chalk and Eagle Ford shale show that these formations are not isotropic, and velocities in loose sand are seen to increase smoothly with depth except for an abrupt increase in compressional speed at the water table. Elastic constants for chalk and shale are computed. A discussion is given of the literature dealing with a packing of spheres as a model for loose sand, and an approximate theory is presented which includes tangential forces between spheres.

INTRODUCTION

Detailed elastic descriptions of near-surface earth materials can be of substantial help in the interpretation of various types of experiments with seismic waves. For example, a knowledge of near-surface layering provides a basis for comparing observed properties of Rayleigh waves with appropriate theoretical treatments. Procedures have been devised which provide suitable elastic descriptions for these purposes, and it is felt that the properties of near-surface earth materials obtained in this way are of some fundamental interest in themselves.

In the experiments to be described, an effort was made to confine the measurements to a small enough region that an assumption of uniformity of earth properties would be justified. Highly localized disturbances are detected by means of geophones or pressure gauges, and velocities are computed as ratios of detector spacings to time intervals obtained from visual comparisons of the observed waveforms. Boreholes permit a systematic variation in the depth at which the measurements are made, and thus a log of earth properties to depths of two or three hundred feet can be obtained.

FIELD PROCEDURES

One experiment requires the use of only one borehole. A blasting cap is fired in the borehole fluid, and the resulting pressure is measured at two shallower depths by crystal gauges. The gauges are usually 15 and 25 feet above the cap. Typical records obtained are shown in Figure 1. The earliest signal shown in Figure 1A indicates a vertically-travelling compressional wave in the formation. The later signal, which causes the trace to go off-scale, is a compressional wave travelling directly up to the borehole fluid. Examples of fluid-borne signals are shown in Figures 1B and 1C.

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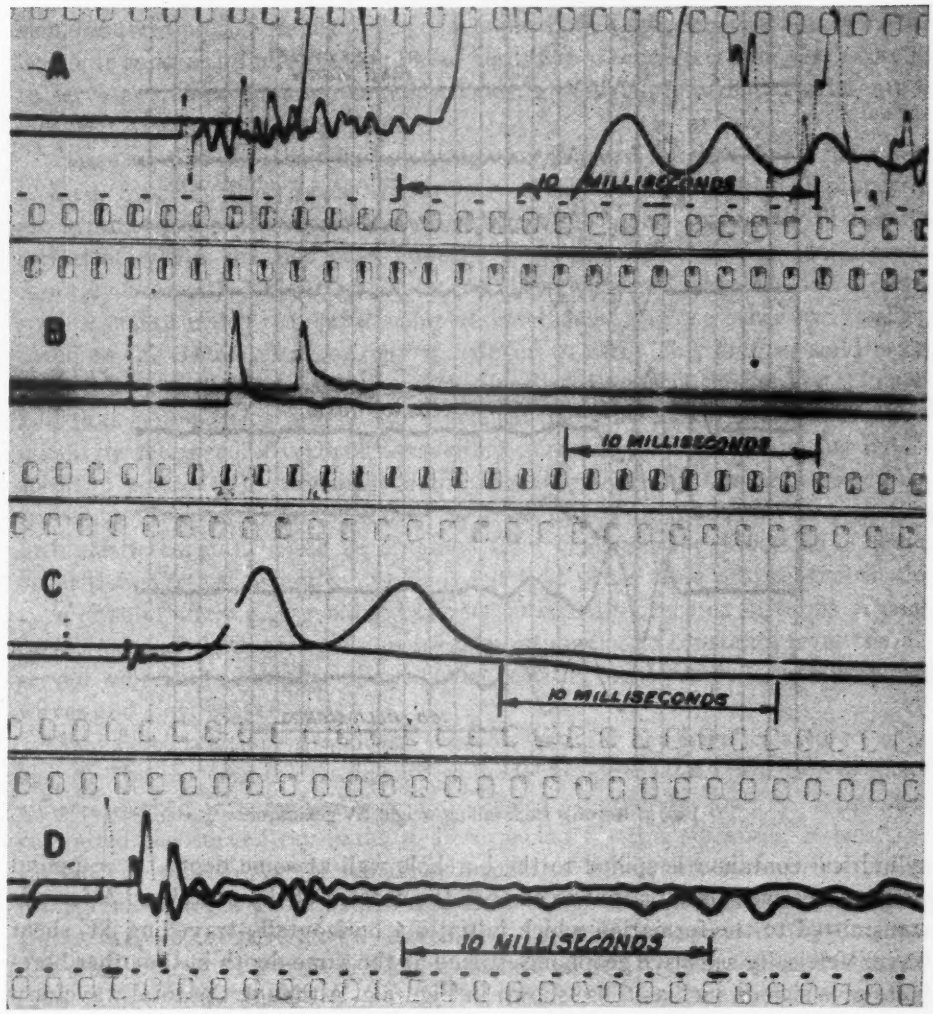

FIG. 1. Typical records from blasting caps. A. Vertically-travelling compressional waves. B. Water pulses in a high-rigidity medium (Austin chalk). C. Water pulses in a lower-rigidity medium (Eagle Ford Shale). D. Horizontally travelling compressional waves.

A second type of measurement requires three boreholes, usually spaced along a line with 10-foot separation. The disturbance due to a blasting cap fired at some depth is observed by means of crystal gauges at the same depth in the adjacent boreholes. Typical records shown in Figure 1D indicate a horizontally-travelling compressional wave in the formation and nothing corresponding to the fluid-borne signal.

The third type of measurement could be done in three holes arranged as above, but frequently five holes in a line with 10 foot spacing have been used. A

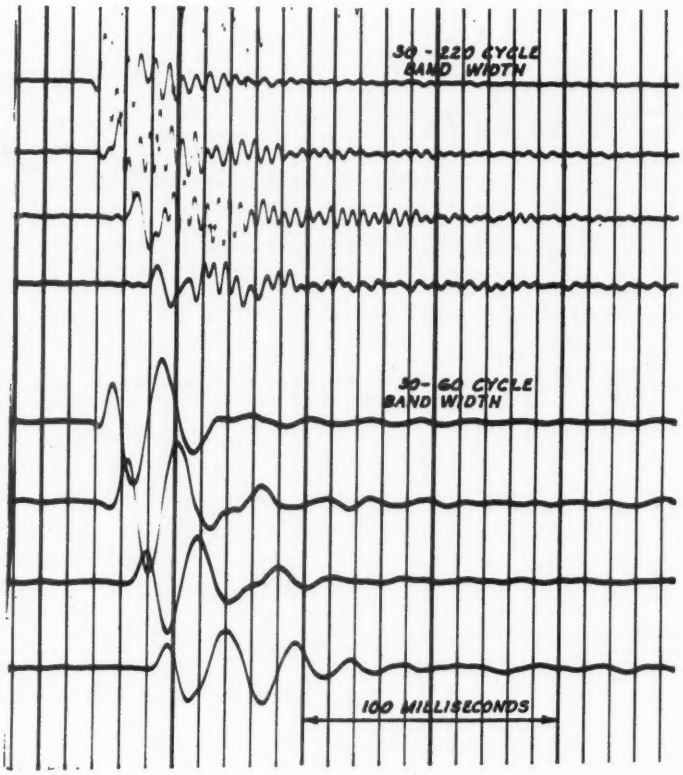

FIG. 2. Records from falling-weight SV generator.

cylindrical container is spiked to the borehole wall at some depth. A 20-pound weight is allowed to fall a foot or so onto the bottom of the container. A force is transmitted to the formation which initiates a horizontally-travelling *SV* shear wave. Vertically-sensitive geophones spiked at the same depth in the other boreholes give signals such as those shown in Figure 2. Although the total waveform from each geophone is rather complex, it is usually possible by means of filters to pick out a portion of the signal which travels at a low speed in good agreement with other indications of *SV* shear speed.

SOME GENERAL CONSIDERATIONS

It is recognized that disturbances created and measured by the procedures described above may result in very complicated records, depending on the nature of the surrounding earth. An effort was made to obtain simple records, first, by confining the experiment to such a small volume that the assumption of homogeneity is generally valid, and second, by choosing sources expected to result in simple elastic waves. Rayleigh[1] described the sound field due to a point compres-

[1] Rayleigh, "Theory of Sound," *Dover Publications*, New York (1945), 418 and 424.

sional source and to a force applied at a point, both applicable to a homogeneous, isotropic solid of infinite extent. These descriptions would certainly be expected to serve as guides for more complex solids, although equivalent treatments of localized sources are not available.

Some aspects of seismic wave propagation in more complex solids have been treated. Stoneley[2] describes a "transversely isotropic" solid in which all properties are symmetrical with respect to a fixed direction. Shales apparently fit this description, where the line of symmetry is perpendicular to the laminations. Stoneley shows that plane waves in any direction must travel at one of three speeds, one of which reduces to compressional speed and the other two to shear speed as the degree of anisotropy is reduced to zero. This kind of solid is described by five elastic constants and the density. Assuming the density is known and that symmetry is referred to a vertical line, one elastic constant is determined by the speed of vertically-travelling compressional waves; another by the speed of horizontally-travelling compressional waves; another by horizontally-travelling *SV* waves; and a fourth by horizontally-travelling *SH* waves. The fifth elastic constant could be obtained from velocities for directions of travel other than vertical or horizontal. It is felt that plane wave propagation in this type of solid offers a reasonable basis for interpreting records in terms of compressional and shear arrivals and for computing elastic constants from the observed velocities. Stoneley shows which elastic constants influence Rayleigh waves and Love waves.

Wave propagation in another type of material has been treated at some length. This material is a mathematical model for loose sand, consisting of elastic spheres packed in a regular way and pressed together by gravity. Gassmann[3] computed the curved ray-paths to be expected for this situation. A local disturbance certainly does not radiate as a spherical wave, and the error in velocity measurement for a given source and detector spacing can be estimated from Gassmann's computed curve. Horizontal velocities determined between two detectors 10 and 20 feet from a source should be pretty good for depths greater than 20 or 30 feet. For shallower depths, measured velocities would be too high unless the spacing is suitably reduced. There is no error in vertical velocity determinations due to curvature of path.

It is, of course, true that horizontal velocities near an interface may be controlled by a refraction path rather than a horizontal path at the depth of measurement. This situation can easily be recognized by inspection of the complete velocity log.

The manner in which the speed of signals travelling in the borehole fluid de-

[2] Robert Stoneley, "The Seismological Implications of Aeolotropy in Continental Structure," *Monthly Notices of the Royal Astronomical Society*, Geophysical Supplement, Vol. 5, No. 8 (1949), 343–353.

[3] Fritz Gassmann, "Elastic Waves Through a Packing of Spheres," *Geophysics*, XVI (1951), 673–685.

pends on the properties of an isotropic solid was treated by Lamb.[4] He derived the result that at low frequencies,

$$c = [\mu B/\rho(\mu + B)]^{1/2} \tag{1}$$

where c is the borehole speed,
B is the bulk modulus of the fluid,
ρ is the density of the fluid,
and μ is the rigidity of the solid.

Borehole speeds are thus measures of the shear rigidity of the formation in which the borehole is drilled if the formation is isotropic. If the formation density is known, the speed of shear waves in the formation can be computed from the rigidity determined in this way. Lamb's result for isotropic solids can be derived very simply from static elasticity. Borehole velocity for a transversely isotropic solid is derived below by this simple method.

Although the results of the procedures described here may at times need interpretation, it is felt that useful descriptions are obtained of the earth materials in which the measurements are made.

Borehole Speed in a Transversely Isotropic Solid

Consider a fluid-filled cylinder of radius a with its axis in the direction of symmetry of a transversely isotropic solid of infinite extent. If the fluid pressure is increased to a value P, the motion in the solid may be assumed to consist of a radial expansion of the form $u_r = Q/r$. This assumption can be checked by substitution into stress-strain relations, and the constant Q can be evaluated by equating stresses at the wall of the cylinder. The appropriate stress-strain relations from Stoneley's article are:

$$\begin{aligned} X_x &= A\frac{\partial u}{\partial x} + (A - 2N)\frac{\partial v}{\partial y} \\ X_y &= (A - 2N)\frac{\partial u}{\partial x} + A\frac{\partial v}{\partial y} \\ Y_x &= X_y = N\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right). \end{aligned} \tag{2}$$

The $x-$ and $y-$ components of the radial displacement are $u = Qx/r^2$ and $v = Qy/r^2$. Equating stresses at the wall of the borehole leads to the following expressions:

$$X_x x^2/a^2 + Y_y y^2/a^2 + 2X_y xy/a^2 = -P. \tag{3}$$

If the stresses, including the appropriate partial derivatives, are substituted into

[4] H. Lamb, "On the Velocity of Sound in a Tube, as Affected by the Elasticity of the Walls," *Manchester Memoirs*, XLII, No. 9 (1898).

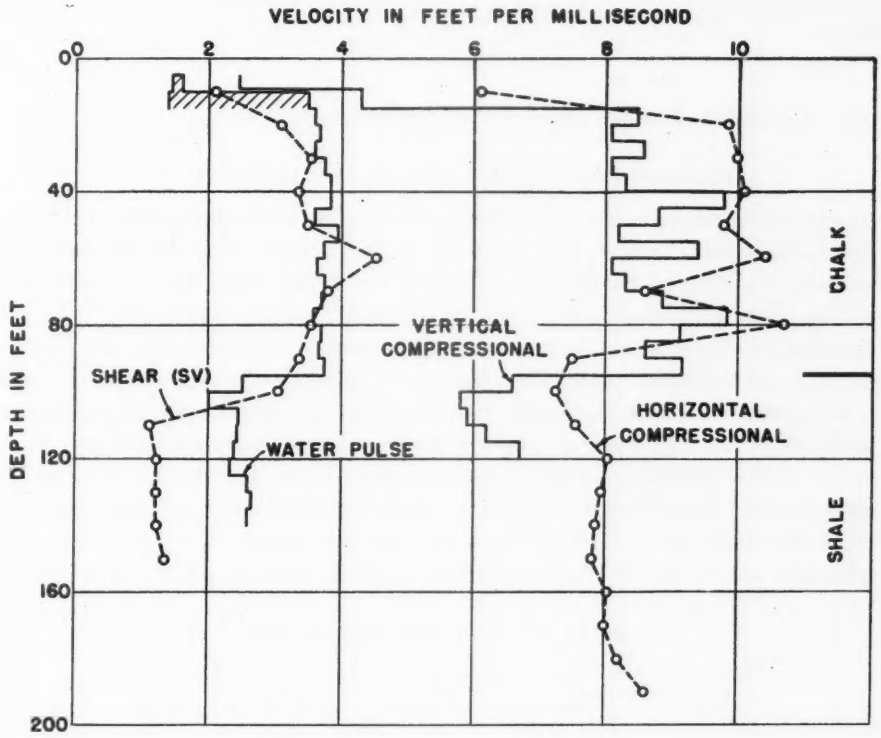

FIG. 3. Velocity logs at the laboratories grounds, Dallas County, Texas.

this equation, the original assumption is seen to be correct if $Q = a^2 P/2N$. N is the elastic constant which controls the speed of horizontally-travelling SH waves in the solid. Hence,

$$u_r = a^2 P/2Nr. \tag{4}$$

If the pressure in the fluid is increased by an amount P, a section originally of length l will be shortened by an amount dl. An elastic constant K opposing this contraction is defined by

$$\pi a^2 dl/\pi a^2 l = -P/K.$$

The section will expand radially, and the net change in volume is the difference between contraction and expansion. The net volume change divided by the original volume depends on the pressure change and the incompressibility B of the fluid.

$$(\pi a^2 dl + 2\pi alPa^2 2/Na)/\pi a^2 l = -P/B.$$

These two relations give

$$K = NB/(N + B). \tag{5}$$

Whence

$$c = [NB/\rho(N + B)]^{1/2}. \tag{6}$$

This is the same as Lamb's result with N replacing μ.

DISCUSSION OF EAGLE FORD SHALE AND AUSTIN CHALK

Figure 3 shows velocity measurements made in boreholes at the Field Research Laboratories, where Austin chalk at the surface is underlain by Eagle Ford shale. Horizontal compressional speeds are higher than vertical compressional speeds in both chalk and shale. In the shale, the *SV* shear speed is seen to be significantly lower than the borehole fluid speed, the latter being only slightly higher than the derived speed for *SH* shear waves. This difference between *SV* and *SH* speeds for Eagle Ford shale was observed at other locations, an example of which is shown in Figure 4. The abrupt increase in compressional speed at a depth of 10 feet corresponds to the ground water level. The driller's log and the change in shear properties at a depth of 60 feet suggest that the shale has been considerably modified by weathering action to this depth.

Average velocities for Austin chalk and Eagle Ford shale are listed in Table I.

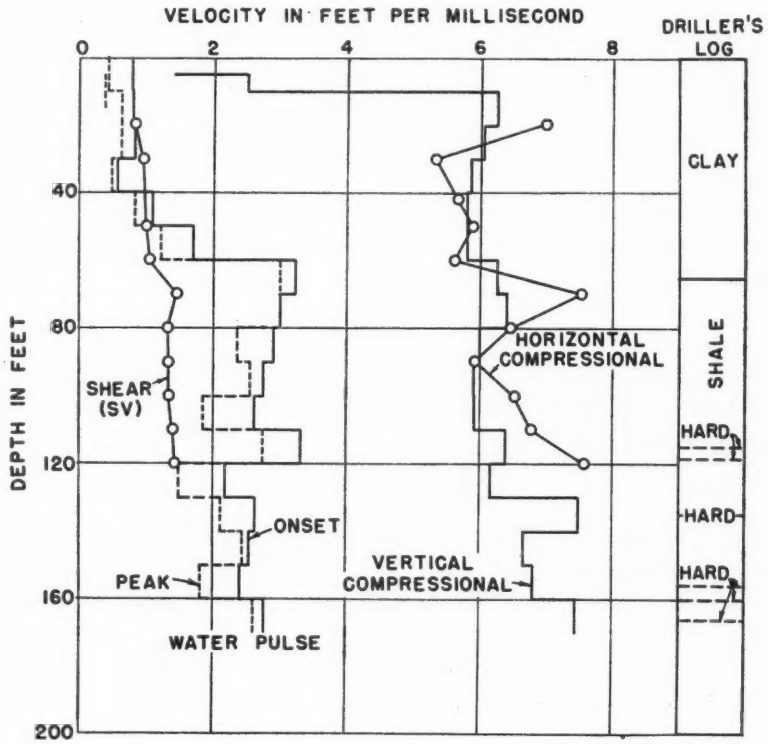

FIG. 4. Velocity logs at Corn Valley Road, Dallas County, Texas.

TABLE I

	Eagle Ford Shale	Austin Chalk
Density	2.0 gm/cm³	2.2 gm/cm³
Horizontal compressional speed	8,000 ft/sec	10,000 ft/sec
Elastic constant A	12×10^{10} dyne/cm²	22×10^{10} dyne/cm²
Vertical compressional speed	6,000 ft/sec	8,500 ft/sec
Elastic constant C	6.5×10^{10} dyne/cm²	14×10^{10} dyne/cm²
SV shear speed	1,250 ft/sec	3,500 ft/sec
Elastic constant L	0.28×10^{10} dyne/cm²	2.4×10^{10} dyne/cm²
Fluid speed	2,500 ft/sec	3,700 ft/sec
Elastic constant N	0.75×10^{10} dyne/cm²	3.1×10^{10} dyne/cm²
SH shear speed	2,000 ft/sec	3,900 ft/sec

Densities obtained from cuttings are also given. Three elastic constants were obtained by multiplying density by the square of the appropriate velocity, and a fourth constant was computed from borehole fluid speed by use of the expression derived above. The derived *SH* speed is also given.

Velocities for both chalk and shale show variation with depth, but when average values are drawn, both formations are obviously anisotropic. All the observations fit the assumption that each of these materials is a transversely isotropic solid, and four of the five elastic constants needed to describe such a solid can be computed. Further measurements might show that even this representation is inadequate to describe the average properties of Austin chalk and Eagle Ford shale.

DISCUSSION OF LOOSE SAND

At several locations where the near-surface material is loose sand, all velocities are found to be very low at the surface, increasing smoothly with depth. Examples are shown in Figures 5 and 6. The rough agreement between horizontal and vertical compressional speeds indicates that there is no marked anisotropy. The *SV* speed shown agrees with *SH* speeds derived from logs of borehole fluid speed, a further indication that loose sand is substantially isotropic.

A plot of derived *SH* speed is given in Figure 6. The ground water level at 50 feet causes an abrupt increase in compressional speed with no perceptible influence on shear properties, a phenomenon which has been observed many times. The solid curves in Figures 5 and 6 are the appropriate velocities of vertically-travelling shear and compressional waves in a hexagonal packing of quartz spheres, computed from Gassmann's expressions with a minor correction discussed below. The constants used for this computation are: density 2.65 gm/cm³, Young's modulus 10^{12} dyne/cm², Poisson's ratio 0.15, all for quartz; and density 1.0 gm/cm³, bulk modulus 2×10^{10} dyne/cm³ for water. The excellent agreement with measured values is somewhat fortuitous, since Gassmann's speeds for horizontally-travelling waves would not agree at all well. However, the dependence of both speeds on the sixth root of the depth and the abrupt increase in compressional speed when the space between the spheres is filled with water

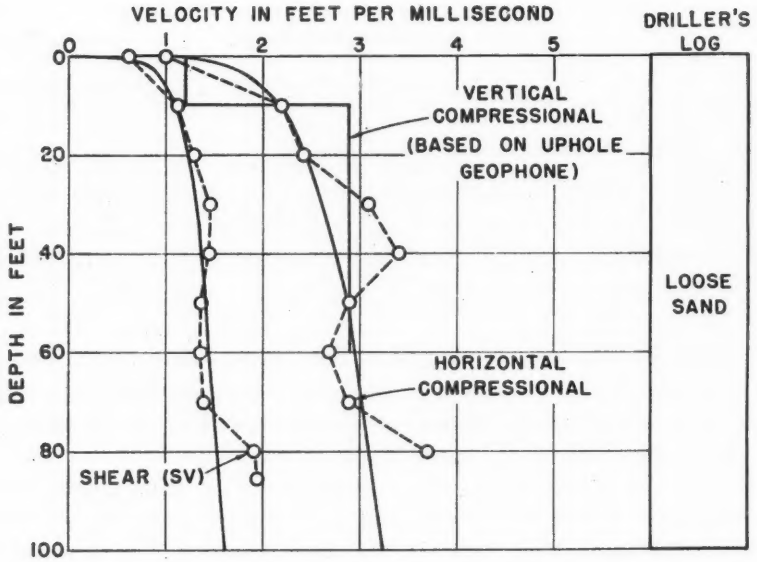

FIG. 5. Velocity Logs at SP 308, T-218 Prospect, Henderson County, Texas.

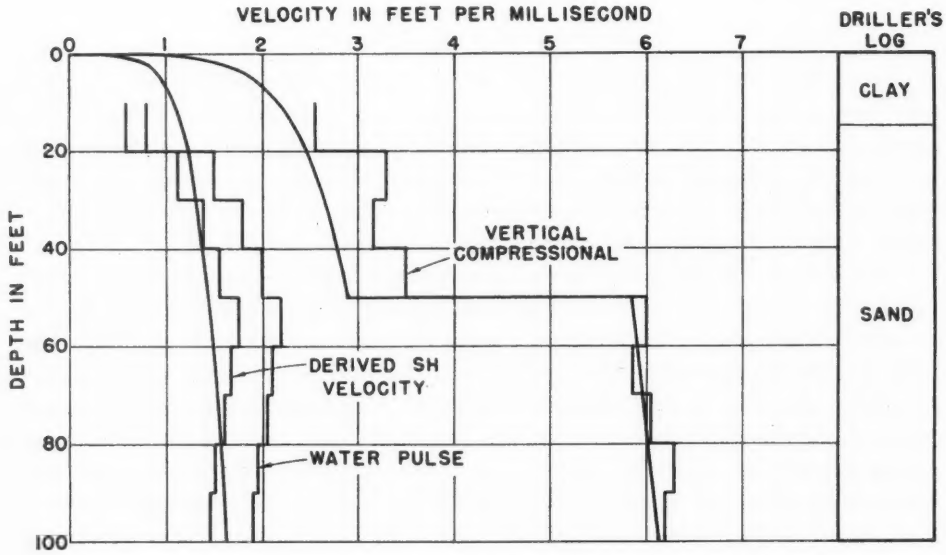

FIG. 6. Velocity Logs at SP 30 A, T-218 Prospect, Henderson County, Texas.

show that a model based on a packing of spheres has a close kinship with loose sand as it occurs in the ground.

THEORIES OF WAVE PROPAGATION IN PACKINGS OF SPHERES

Hara[5] discussed the velocity of sound in a packing of spheres, but all his expressions for velocity are dimensionally incorrect. Iida[6] included the effect of gravity and compared laboratory measurements on columns of sand with derived expressions for velocity, but his expressions are unsatisfactory in some respects. Gassmann recently published a derivation of both shear and compressional speeds in a hexagonal packing of spheres pressed together by gravity, with the pore spaces either empty or filled with fluid.

All of these theories make use of a basic relationship which was worked out by Heinrich Hertz prior to 1881 and reprinted in his collected works. The source used here is Timoshenkos' discussion of Hertz's theory.[7] A force P causes the centers of two identical spheres to approach each other by an amount S. The spheres are characterized by Young's modulus E, Poisson's ration ν, and density ρ. The area of contact is shown to be a circle of radius a, and the following relationships are derived:

$$a = [3(1 - \nu^2)RP/4E]^{1/3}, \tag{7}$$

$$S = [9(1 - \nu^2)^2P^2/2E^2R]^{1/3}. \tag{8}$$

The latter represents a nonlinear spring, since the displacement is not directly proportional to the force. For incremental changes around a preloaded value, the stiffness of this spring is the ratio of incremental force to incremental displacement.

$$\frac{dP}{dS} = [3E^2RP/4(1 - \nu^2)^2]^{1/3}. \tag{9}$$

Gassmann assumed that spheres in contact remain spherical except for the actual circles of contact, where they are flat. As a matter of fact, the spheres are deformed in the neighborhood of the circles of contact. The displacement between centers of spheres for a given load is just twice as large as Gassmann assumed, and for this reason, Gassmann's derived speeds are too high by $\sqrt{2}$.*

The above expressions are exact mathematically and form a basis for stress-strain relationships in a granular substance when the forces act normal to the spherical surfaces at the points of contact. Such forces would exist in a simple cubic packing of spheres for a plane seismic wave traveling along one of the cubic axes. In general, however, forces and displacements would not be in the direction

[5] G. Hara, "Theorie der Schwingungs-ausbreitung in Gekornten Substanzen und experimentelle Untersuchungen in Kohlepulver," Elektrische Nachrichten Technik, Vol. 12 (1935), 191–200.

[6] Kumizi Iida, "Velocity of Elastic Waves in a Granular Substance," Bull. of the Earthquake Research Institute, Vol. 17, part 4 (1939), 783–807.

[7] S. Timoshenko, "Theory of Elasticity," McGraw-Hill Book Co., New York (1934).

* Editor's note: see p. 269 this issue.

of a line connecting centers of spheres, and tangential components would be expected. Elastic distortions due to tangential forces influence the stress-strain relationships, and these are not described by Hertz. The most nearly applicable expression found in the literature so far is an equation given by Mindlin[8] stating the static displacements in a semi-infinite solid due to a point tangential force acting at the surface of the solid. The tangential forces between spheres in contact are undoubtedly distributed over the circle of contact, and an exact treatment would involve a derivation of this force distribution and of the resulting displacements in the spheres. An approximate expression is derived below, based on assumptions which are evaluated to some degree.

Compressional Waves in a Simple Cubic Packing of Spheres

A cubic packing is not a realistic model of sand because it is not mechanically stable, but velocities derived for such a packing illustrate the viewpoint in a very simple way. The treatment is confined to wave-lengths which are very long compared with grain dimensions. The viewpoint consists of deriving an elastic modulus statically for a representative elementary volume and dividing it by the average density for the same elementary volume. The square root of this ratio gives the appropriate velocity.

Plane compressional waves involve normal stresses in the direction of propagation and displacement occurring only in this direction. For simplicity, this direction is taken to be one of the cubic axes. The cube $2R$ on an edge contains one sphere and can be considered a typical elementary volume. The force per unit area divided by the change in length per unit length is the elastic modulus desired.

$$K = \frac{dP}{dS}/2R = [3E^2P/32(1 - \nu^2)^2R^2]^{1/3}. \tag{10}$$

If the loading force is provided by gravity, then it consists merely of the weight of the spheres directly above the one being considered. If the depth of the sphere is Z, then,

$$P = (4\pi R^3/3)\rho_0 g(Z/2R) = 2\pi R^2\rho_0 gZ/3. \tag{11}$$

Substituting this in (10),

$$K = [\pi\rho_0 gE^2Z/16(1 - \nu^2)^2]^{1/3}. \tag{12}$$

The average density is the mass of one sphere divided by the volume of the cube it effectively occupies, or

$$\rho = \pi\rho_0/6. \tag{13}$$

[8] R. D. Mindlin, "Force at a Point in the Interior of a Semi-Infinite Solid," *Physics*, Vol. 7 (1936), 195–202.

The compressional velocity for cubic packing then is

$$V_p = 3^{1/2}E^{1/3}g^{1/6}Z^{1/6}/2^{1/6}\pi^{1/3}\rho_0^{1/3}(1 - \nu^2)^{1/3}. \quad (14)$$

One notable result is that the velocity approaches zero near the free surface and increases as the sixth root of the depth. It should also be noted that the result does not depend on the radius of the spheres.

Displacements Due to Tangential Forces

A plane shear wave traveling along a cubic axis is characterized by tangential stresses on the contact surfaces and displacement perpendicular to the axis. The

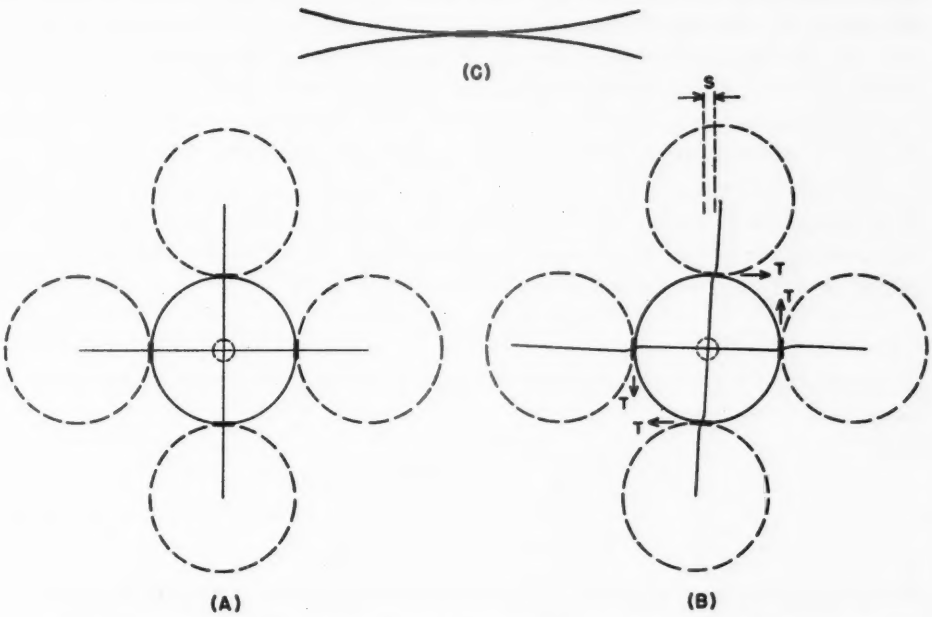

FIG. 7. Geometry for Tangential Forces in a Cubic Packing of Spheres. A. Spheres at rest. B. Spheres displaced by tangential force T. C. Circle of contact at depth of 300 feet.

geometry is the same for compressional waves, and the forces acting on a single sphere are shown in Figure 7. Forces on the front and back contact circles have a negligible effect on the force-displacement relationships. The tangential force at the top must be matched by an equal and opposite force at the bottom for static equilibrium. These forces constitute a couple which can be matched by an opposite couple due to neighboring spheres. Friction between spheres is necessary for these forces to be exerted. An equation is here derived which gives the relative displacement u between the upper and lower contact points as a function of the applied force T.

Mindlin published relations between a force parallel to the surface of a semi-

infinite solid applied at a point in the solid and the resulting displacements. When the force is applied at the free surface, the component of displacement parallel to the force and existing at other points on the free surface simplifies to the following equation:

$$\mu = T(1 - \nu \sin^2 \theta)/2\pi\mu r. \tag{15}$$

T acts at the origin in the positive r direction for $\theta = 0$. μ is shear modulus.

If a rigid disc of radius a is assumed to be in slipless contact with the free surface and a total force T is applied to the disc, a displacement U results which is constant over the area of the disc because of its assumed rigidity. Some stress distribution over the disc is set up which may depend on r' and θ' and which must integrate over the disc to the total force T. This distribution of tangential force per unit area should be multiplied by Equation (15) and integrated to give the displacement U. No exact distribution was found by trial and error, so the following approximate one is described. First, Poisson's ratio is considered small enough that $(1-\nu \sin^2 \theta)$ in Equation 15 can be considered unity. This is pretty good for quartz spheres, where ν is about 0.15. This requires that the force distribution be independent of angle, which suggests that a term is being neglected which is the same order of importance as the $\nu \sin^2 \theta$ term above. Then, the force is assumed to vary as the square of the radius,

$$t = Ar'^2.$$

A is evaluated by integrating over the area of the disc and equating to the total force.

$$\begin{aligned} T &= \int_0^a \int_0^{2\pi} Ar'^2 r' d\theta' dr' = \pi a^4 A/2, \\ t &= 2Tr'^2/\pi a^4. \end{aligned} \tag{16}$$

The displacement at any point can be obtained from the following integration:

$$u = \int_0^a \int_0^{2\pi} 2Tr'^2 dr' r' d\theta'/2\pi^2 a^4 \mu r,$$

where r' and θ' are coordinates with the origin at the center of the disc and r is measured from the point in question as an origin. Graphical integration showed that the displacement is not constant, showing the assumed stress distribution to be incorrect. However, the departure is small enough that a useful result is obtained by accepting the stress distribution as approximately correct. The displacement at the center of the disc is

$$U = \int_0^a \int_0^{2\pi} Tr'^2 dr' d\theta'/\pi a^4 \mu = 2T/3\pi\mu a. \tag{17}$$

This is a linear spring with a stiffness constant given by

$$\frac{dT}{dU} = 3\pi\mu a/2. \tag{18}$$

Shear Waves in a Simple Cubic Packing of Spheres

A sphere in a cubic packing is in contact with six neighbors as shown in Figure 7. The circles of contact are much smaller than shown, the radius being about 3 percent of the radius of the sphere at a depth of 300 feet and, of course, being smaller at shallower depths. Figure 7C gives the proportions in the extreme case. Because the circle is small, an assumption is made which is undoubtedly good at shallow depths and is probably pretty good to a depth of 300 feet or more. This assumption is that tangential forces applied over the circle of contact cause displacements relative to the body of the sphere which are the same as if the circle were on a plane rather than a curved surface. This implies that the spheres maintain their shape except for distortions in the immediate neighborhood of each circle of contact.

If a tangential force T is applied on the top contact circle as shown in Figure 7B, a local displacement U results and the sphere moves a local displacement of U at this point, also. The sphere rotates until the couple due to top and bottom forces is balanced by forces T on the side circles as shown, and this results when a displacement of U has been achieved at each circle. The relative displacement between the top and bottom circles is U at the top plus U at the bottom plus $2U$ due to rotation, or a total of $4U$.

Using Equation (18),

$$\frac{dT}{dS} = 3\pi\mu a/8. \tag{19}$$

To get an elastic modulus,

$$K' = \frac{dT}{dS}/2R = 3\pi Ea/32(1+\nu)R. \tag{20}$$

Making use of Equations (7) and (11), the following expression is derived which is comparable with (12) for compressional waves.

$$K' = [3\pi(1-\nu)/16][\pi E^2\rho_0 gZ/16(1-\nu^2)^2]^{1/3}. \tag{21}$$

The velocity is obtained from (21) and (13).

$$V_s = 3\pi^{1/6}(1-\nu)^{1/2}E^{1/3}g^{1/6}Z^{1/6}/4(1-\nu^2)^2 2^{1/6}\rho_0{}^{1/3}. \tag{22}$$

This is the speed of shear waves in a simple cubic packing.

Effect of Water Saturation

If one assumes that enclosed fluid and sand particles move together in a compressional wave, the speed can be computed very simply from static considera-

tions. Displacement of one face of an elementary cube causes volume compression of the fluid and of the solid grains and also deforms the matrix of grains in contact. Hence there are two stiffnesses opposing the motion. The first is

$$B_c = \frac{1}{\dfrac{(1-n)}{B_g} + \dfrac{n}{B_l}}, \quad \text{where} \tag{23}$$

n is porosity, B_g is bulk modulus of the grains, and B_l is bulk modulus of the liquid. The second (for cubic packing) is the same as (12) except for substitution of $(\rho_0 - \rho_l)$ for ρ_0 because of the buoyant effect of the fluid,

$$K_l = [\pi(\rho_0 - \rho_l)gE^2Z/16(1-\nu^2)^2]^{1/3}. \tag{24}$$

The appropriate compressional modulus is the sum of the two above stiffnesses.

$$K_s = B_c + K_l.$$

The density of the saturated medium is

$$\rho_s = (1-n)\rho_0 + n\rho_l,$$

and the speed is

$$V_p \text{ (saturated)} = [K_s/\rho_s]^{1/2}.$$

For cubic packing, $n = (1 - \pi/6)$, and the speed for compressional waves is:

$$V_p \text{ (sat)} = \left[\frac{\dfrac{1}{\dfrac{(\pi/6)}{B_g} + \dfrac{(1-\pi/6)}{B_l}} + \dfrac{\pi(\rho_0 - \rho_l)gE^2Z^{1/3}}{16(1-\nu^2)^2}}{(\pi/6)\rho_0 + (1-\pi/6)\rho_l} \right]^{1/2}. \tag{25}$$

The more refined derivation by Gassman makes the same assumption of grains and fluid moving together and comes out with the expression for hexagonal packing equivalent to the above equation for cubic packing.

Usefulness of This Model

It must be significant that the computed dependence of speed on the sixth root of the depth and the increase in compressional speed at the water table agrees so well with measurements. However, none of the treatments of packings of spheres is satisfactory in detail. Tangential forces must be a factor in the behavior of sand particles. Such forces result in sliding between spheres near the peripheries of the circles of contact, thus providing a means of introducing sliding friction as a source of attenuation. Although the treatments discussed here can hardly be extrapolated to the depths and types of materials discussed by Faust,[9]

[9] L. Y. Faust, "Seismic Velocity as a Function of Depth and Geologic Time," *Geophysics*, Vol. XVI (1951), 192.

his dependence of velocity on the sixth root of the depth suggests that some extension of this type of approach should be applicable to sands and shales at great depths.

ACKNOWLEDGEMENTS

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ON THE PROPAGATION OF RAYLEIGH WAVES ON THE SURFACE OF A VISCO-ELASTIC SOLID*

C. W. HORTON†

ABSTRACT

The propagation of Rayleigh waves over the surface of a visco-elastic solid is examined. It is shown that for a Poisson solid ($\lambda=\mu$), the behavior of the waves can be characterized by a dimensionless parameter $\delta=\omega\eta/\mu$ which is less than 0.1 for the frequencies and elastic parameters of interest in geophysics. In this expression ω=angular frequency, μ=shear modulus, η=viscosity. For small values of δ it is possible to modify the usual analysis of Rayleigh waves and obtain the new characteristics without much difficulty. It is shown that the motion of a particle on the earth's surface is changed from an ellipse to a Lissajous' figure and that the phase angle between the vertical and horizontal displacements is changed from $\pi/2$ to $(\pi/2)-0.1488\delta$ radians. The surface wave has an attenuation factor of $2.908\delta/\lambda_0$ where λ_0 is the wave length of the Rayleigh wave in the absence of internal friction.

INTRODUCTION

It is often assumed for the purpose of analysis that the earth behaves like a visco-elastic solid. While this assumption is probably false (Born, 1941), the theoretical predictions agree fairly well with observations at low frequencies. A well known example of this statement is the prediction by Gutenberg (1929) of the relationship between the dominant period of a seismic disturbance and the distance travelled. Experimental verification of this formula has been given by Harris and Haskell (1940), among others. Consequently one feels confident that a study of Rayleigh waves at the surface of a visco-elastic solid has some relevance for the geophysical problem.

Leet (1946) and Howell (1949) have shown paths and velocities associated with Rayleigh waves in which the motion is that of a Lissajous' figure which leans away from the source. It is the purpose of the present investigation to determine if internal friction will produce the necessary modification of the classical Rayleigh motion to explain these observations.

Gutenberg and Schlechtweg (1930) have shown that if the shear modulus μ be replaced by the operator $\mu+\eta\partial/\partial t$, and if one requires that the spur, Θ, of the stress matrix and the spur, θ, of the strain matrix be related by $\Theta=(3\lambda+2\mu)\theta$ as in the theory of ideal elasticity, the other Lame constant must be replaced by the operator $\lambda-(2/3)\eta\partial/\partial t$.

Scholte (1947) examined the problem of Rayleigh waves and showed that the velocity is governed by eq. (1) below. Caloi (1946, 1948) has carried through the analysis and has computed values for the velocity, the attenuation, and the displacement associated with Rayleigh waves. In the present paper it is shown that Caloi's results can be obtained very simply when the parameter δ is small.

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THE ROOTS OF THE CUBIC EQUATION

It is well known that the velocity of a periodic Rayleigh wave is determined by one of the roots of the cubic equation (Macelwane and Sohon, 1936).

$$s^3 - 8s^2 + 8(3 - 2n)s - 16(1 - n) = 0, \tag{1}$$

where

$$s = (V_{\text{Rayleigh}}/V_{\text{shear}})^2 \tag{2}$$

and

$$n = \mu/(\lambda + 2\mu).$$

In the case of a periodic wave with a time factor $\exp(-i\omega t)$ in a visco-elastic solid, one has

$$n = (\mu - i\omega\eta)/[(\lambda + 2\mu) - i(4/3)\omega\eta]. \tag{3}$$

If the discussion is restricted to a Poisson solid for which $\lambda = \mu$, and if a dimensionless parameter

$$\delta = \omega\eta/\mu \tag{4}$$

is introduced, then one has

$$n = (1 - i\delta)/[3 - i(4/3)\delta]. \tag{5}$$

In the case of the earth and the surface waves that have been observed, δ is always less than 0.1. For example in earthquake studies ω for surface waves is usually between 0.5 and 5 while η and μ are approximately 5×10^9 and 3×10^{11} cgs units, respectively (Gutenberg, 1939). In seismic exploration ω for the surface waves varies from 30 to 90 while η and μ are approximately 10^7 and 10^{10} cgs units, respectively. In this instance δ falls between 0.03 and 0.09.

For small δ the root s of eq. (1) that is of interest will not differ much from the root $s_0 = 2(1 - 1/\sqrt{3}) = 0.8453$ for the case $\eta = 0$. This suggests the possibility of expanding the expression on the right of eq. (5) as a power series in δ and neglecting the squared and higher powers. Set

$$s = s_0 + z \tag{6}$$

and neglect powers of z higher than the first and cross products of the from $z\delta$. When this is done, eq. (1) reduces to a linear equation in z which can be solved readily. The result is

$$s = 0.8453 + i0.06289\delta, \tag{7}$$

or by virtue of eq. (2),

$$V_{\text{Rayleigh}} = 0.9194(1 + i0.03720\delta)V_{\text{shear}}. \tag{8}$$

It should be remembered that

$$V_{shear} = (\mu/\eta)^{1/2}(1 - i\delta)^{1/2}. \tag{9}$$

Some idea of the validity of eq. (7) may be obtained by comparing values derived from it with the more accurate results obtained by Caloi (1948). According to Caloi if $\delta = 0.1047$, $s = 0.8453 + i0.00659$ while eq. (8) yields $s = 0.8453 + i0.00658$.

If no restriction be made on the range of δ, eq. (1) defines s as a function of δ with $0 \leqq \delta \leqq \infty$. Figure 1 shows a curve in the complex s-plane, $s = x + iy$, which represents the values of s which are relevant for a Rayleigh wave. The points

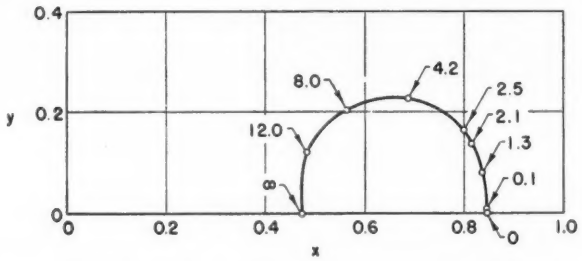

FIG. 1. Plot of the complex root s ($s = x + iy$) of the cubic equation as a function of the parameter δ. The circles are computed values corresponding to the values of δ that are indicated.

corresponding to $\delta = 8.0$ and 12.0 are new while the other values are taken from the paper by Caloi (1948).

THE MOTION OF A SURFACE PARTICLE

Macelwane and Sohon (1936) show that the horizontal and vertical (positive downwards) displacement of a surface particle during the passage of a Rayleigh wave are given by

$$u = P_1 e^{-i\omega t + ikr + i\pi/2} \tag{10}$$

and

$$w = P_2 e^{-i\omega t + ikr}$$

respectively, where

$$\frac{P_2}{P_1} = \frac{1 - (s/2)}{(1 - s)^{1/2}}. \tag{11}$$

If the value of s given by eq. (7) is substituted into (11) and the resulting expression expanded in powers of δ, one has

$$(P_2/P_1) = 1.468(1 + i0.1488\delta) \tag{12}$$

if powers of δ higher than the first are neglected. It is evident that when $\delta = 0$, (10) and (12) describe the well known retrograde elliptic motion in which the vertical displacement w leads the horizontal displacement by $\pi/2$ radians. How-

ever when δ is different from zero, this phase difference is reduced to $(\pi/2) - 0.1488\,\delta$ radians. This means that the path of the particle is changed from an ellipse to a Lissajous' figure but the change is too slight to be significant.

It is of interest to compare the values obtained by this simple approach with those obtained by a rigorous calculation. If $\delta = 0.0628$, Caloi shows that the phase difference between the vertical and horizontal motion is $(\pi/2) - 0.00934$ radians while the formula just cited gives a value of $(\pi/2) - 0.00935$ radians. When $\delta = 0.1047$, Caloi obtains a value of $(\pi/2) - 0.0124$ while the present formula yields $(\pi/2) - 0.0156$.

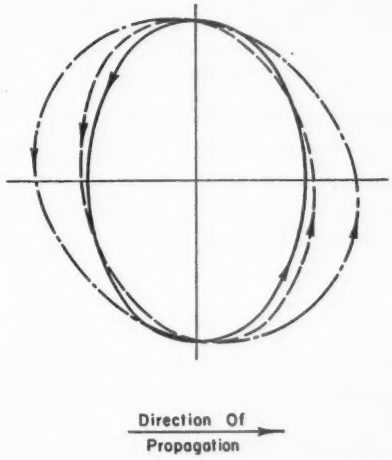

FIG. 2. Earth particle paths for three values of δ. The solid curve is for $\delta = 0$ and is an ellipse. The next two curves, in order of increasing horizontal displacement, are for δ equal to 1.26 and 4.12, respectively. Each curve has been adjusted so that the maximum vertical displacement is unity.

Figure 2 contains a plot of the trajectories of a surface particle for various values of δ. The trajectory for the case $\delta = 0.25$ differs at most from the true elliptical motion (solid curve) by the width of the curve. Although earth particle paths have been observed by Leet (1931) which are similar to the widest curve shown in Figure 2, it is unlikely that the explanation is visco-elasticity. The axis of the Lissajous' figure shown in Figure 2 leans towards the source which is contrary to the observations cited in the introduction.

THE COMPLEX PROPAGATION CONSTANT

The last variable that needs to be considered is the complex propagation constant, k, which may be defined as

$$k = \omega/V_{\text{Rayleigh}} = (\omega/V_{\text{shear}})s^{-1/2}. \tag{13}$$

By virtue of eqs. (7), (8), and (9) and the usual approximation regarding higher powers of δ one can obtain the following result:

$$k = (2\pi/\lambda_0) + i2.908\delta/\lambda_0. \qquad (14)$$

Here λ_0 is the wave length of the Rayleigh wave in the same medium in the absence of internal friction. Equation (14) may be summarized as follows. The presence of a small amount of internal friction does not change the velocity of propagation perceptibly but it does introduce an attenuation of 25.3δ db per wave length.

These results can be compared with those obtained by Caloi. When $\delta = 0.1407$, Caloi obtains a velocity which is 1.004 times the velocity of the Rayleigh wave in the absence of internal friction. Caloi obtains a value of 0.303 for the attenuation factor per wave-length while eq. (14) yields the value 0.305.

SUMMARY

The preceding discussion shows that internal friction does not produce a significant change in either the velocity or the shape of the earth particle path for any value of δ that will be encountered in geophysical applications. The attenuation that is predicted is large enough to be observable. The comparison with the rigorous formulae of Caloi shows that the simple formulae obtained in this paper are satisfactory for values of δ less than 0.1.

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THE VELOCITY AND RAY PATHS OF SOUND WAVES IN DEEP SEA WATER*

KARL DYK† AND O. W. SWAINSON‡

ABSTRACT

Basic experiments conducted by the U. S. Coast and Geodetic Survey in 1933 and 1934 to determine the ray paths of sound in sea water are reported. Time-distance, frequency, and amplitude measurements were obtained both in deep sea and shallow waters off the California coast. The mean velocity from a depth of 30 fathoms to a depth of about 1000 fathoms agreed with predictions within a few meters per second. The data indicate a velocity of 1,580 meters per second in the mud-floor at the experimental site. A high velocity near the source was indicated and the underwater explosion acted as a multiple source. A maximum of five reflections was observed, and diffraction was a factor in the observance of reflections beyond certain critical distances as a result of ray curvature. Direct paths along the surface were also limited by ray curvature. Direct transmission along a narrow (nearly) constant velocity layer at a depth of 100 fathoms was found, but direct transmission along the 400-fathom velocity inversion could not be definitely established although it seemed highly probable. The direction of first motion associated with several ray paths showed a gradual change of sign with increasing distance.

INTRODUCTION

Basic experimental work on the propagation of sound in sea water was conducted by the United States Coast and Geodetic Survey in the Santa Barbara Islands Basin off the coast of Southern California during November of 1933 and again in December of 1935. The experiments were undertaken to improve techniques in radio acoustic ranging (RAR), an acoustic triangulation method with which geophysicists are generally familiar. Results of the earlier work appeared in a special publication of the Survey in April 1934,[1] and of the latter in the December 1936 issue of the Field Engineers Bulletin[2] (U.S.C. & G.S.). While copies were issued to persons then interested in the field, circulation was limited.

The last war stimulated research in submarine acoustics. The search for oil in the Gulf of Mexico by seismic methods has also broadened interest in the field. As similar work has not been reported in the literature, it is felt that wider distribution of the Survey's reports is now desirable. The contents are here presented in essentially their original form and meaning. Deletions of material not of general interest, and rearrangements in the interest of brevity and clarity have, however, been made.

* Manuscript received by Editor June 21, 1951.

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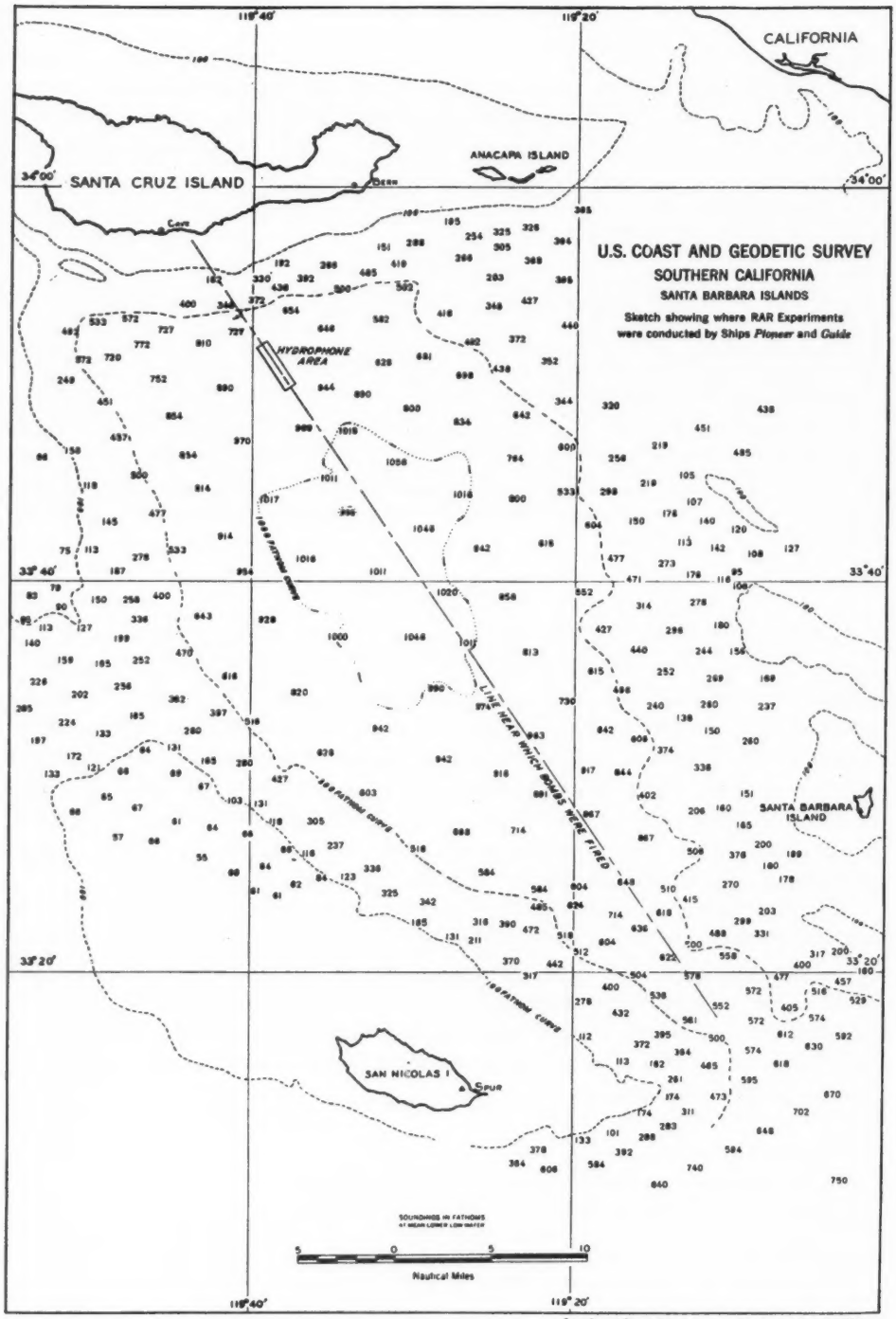
[1] Swainson, O. W. (C. G. McIlwraith and Karl Dyk), *The Velocity and Ray Path of Sound in Deep Sea Water*, U. S. Dept. of Commerce, Coast and Geodetic Survey (April 1934).

[2] Swainson, O. W., *Velocity and Ray Paths of Sound in Deep Sea Water*, Field Engineers Bulletin, U.S.C. & G.S. (Dec. 1936), 1–64.



From Special Report of O. W. Swainson, Commanding Ship PIONEER
U. S. Coast and Geodetic Survey Print

FIG. 1

OUTLINE OF THE PROGRAM

The project was carried out by the U.S.C. & G.S. ship *Pioneer*, commanded by Captain O. W. Swainson, and assisted by the U.S.C. & G.S. *Guide*, Captain F. H. Hardy commanding the first year, and Captain F. L. Peacock the second year. Karl Dyk was attached to the *Pioneer* to analyze and interpret the acoustic data.

Bombs were fired from the *Guide* and recordings made on the *Pioneer* from two hydrophones at different depths. Distances varied from about five to 85 kilometers. Ship positions were determined at the time of firing of the bombs and at the time of arrival of the resulting sound at the hydrophones by observers with theodolites located at triangulation stations on shore. Time breaks were transmitted by radio.

Due to unfavorable weather, very few fixes on the two ships were obtained during the 1933 work. However, a large number of records were obtained for distances of from about 18 to 60 kilometers. As the conclusions based on these incomplete data were confirmed by the subsequent work which had good distance control, they will not be repeated here.

The site of the experiments is shown in Figure 1. Two different sets of conditions are being reported: (a) Charges fired near the surface and at various depths in water down to 1,020 fathoms in depth with the hydrophones also in deep water, one at 30 fathoms and the other at various greater depths; distances be-

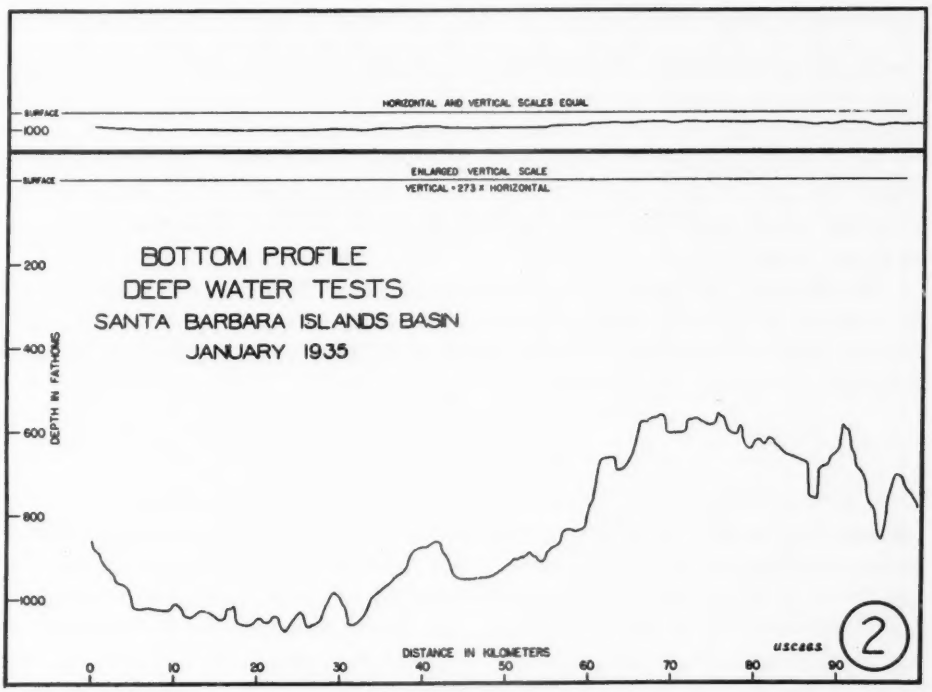


FIG. 2

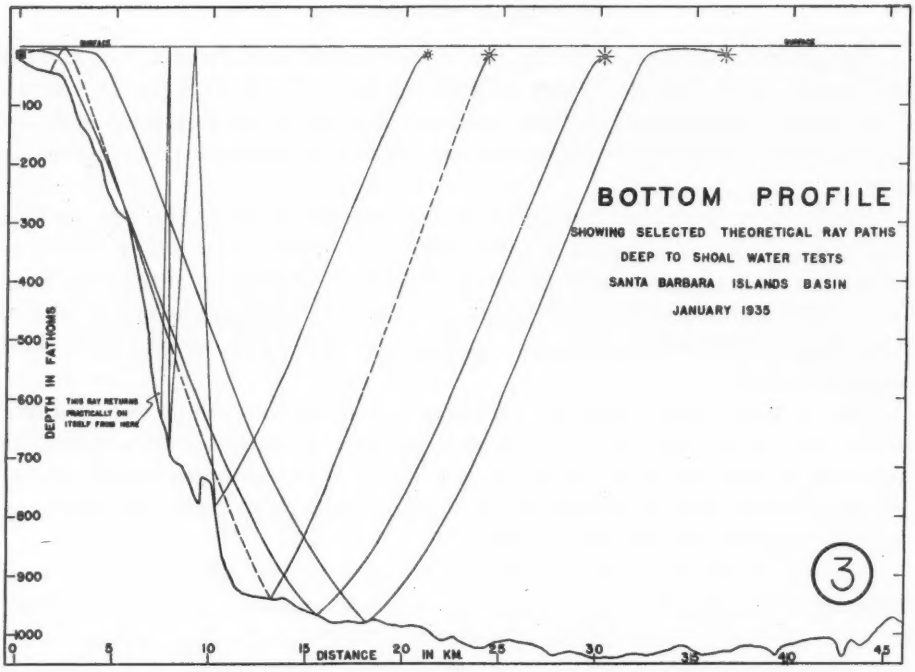


FIG. 3

tween charge and hydrophones ranged from four to 75 kilometers. (b) Charges fired at various depths in deep water with one hydrophone at 30 fathoms in shoal water; distances ranged from two to 46 kilometers.

In each case electrically detonated 4-ounce bombs were fired with the bombing vessel stationary, and fused 8-ounce bombs were thrown overboard with the bombing vessel underway. The fused bombs were timed to detonate at a depth of about 10 fathoms.

Two lines of fathometer soundings were run over the path of the experiments in order to supplement depths obtained by previous hydrographic surveys. The bottom profiles along these lines are shown in Figures 2 and 3. Fathometers were calibrated by means of wire line soundings.

INSTRUMENTATION

The underwater sounds were received by non-directional hydrophones. After vacuum tube amplification the sounds were photographically recorded by a two-string oscillograph with time-marks every 0.01 second. A separate measure of the travel time was made by conventional radio acoustic ranging chronographs with time-marks every second. Usually only fractional seconds were recorded on the oscillograph; i.e., it was turned off between the arrival of the initial and the onset of the bomb noises to save photographic paper.

Frequency and phase characteristics of the recording systems were not de-

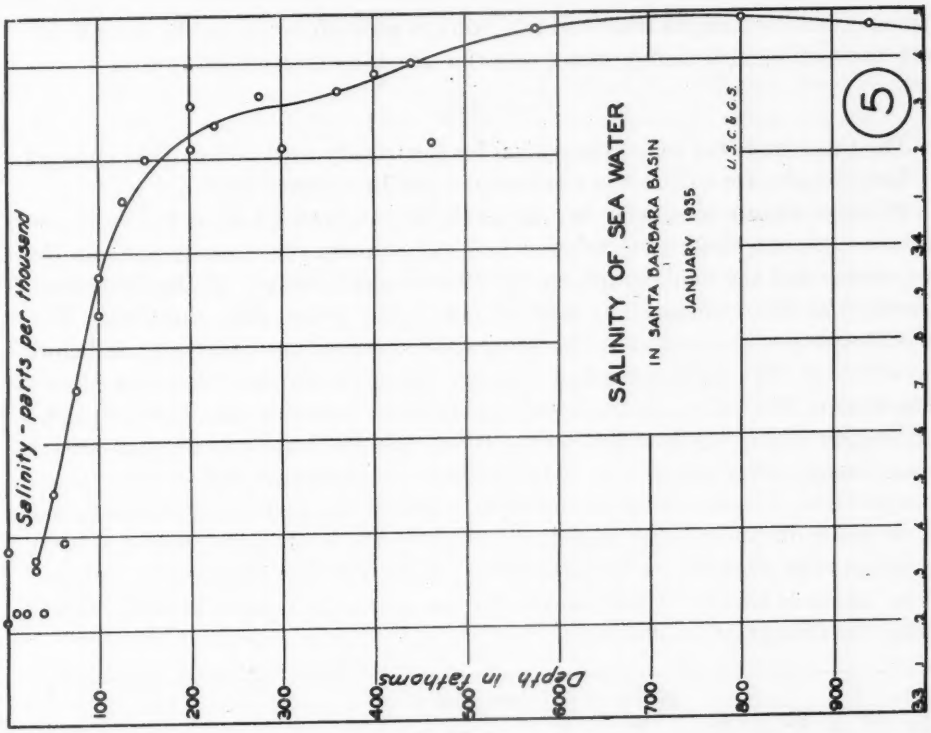

Salinity - parts per thousand
Depth in fathoms
SALINITY OF SEA WATER
IN SANTA BARBARA BASIN
JANUARY 1935
U.S.C.&G.S.
5

FIG. 5

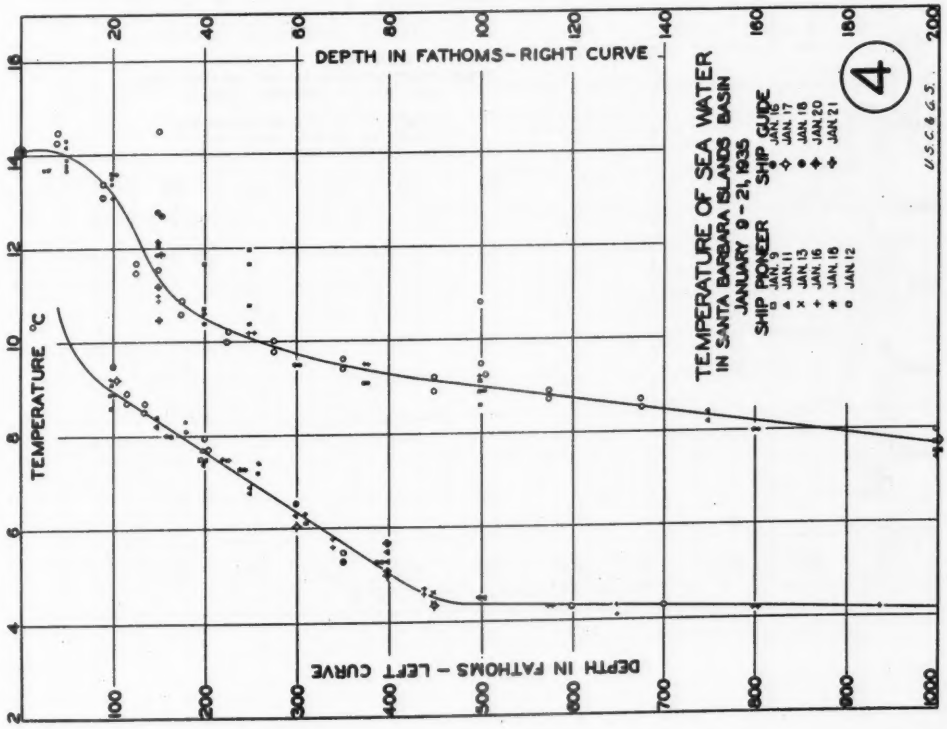

TEMPERATURE °C
DEPTH IN FATHOMS - LEFT CURVE
DEPTH IN FATHOMS - RIGHT CURVE
TEMPERATURE OF SEA WATER
IN SANTA BARBARA ISLANDS BASIN
JANUARY 9 - 21, 1935
SHIP PIONEER
SHIP GUIDE
JAN. 9
JAN. 11
JAN. 13
JAN. 16
JAN. 16
JAN. 12
JAN. 17
JAN. 18
JAN. 20
JAN. 21
U.S.C.&G.S.
4

FIG. 4

termined, but frequencies from 100 to 1,500 cps were observed on the recordings. Both the oscillograph timing motor and the chronometer were calibrated.

PROCEDURE

The procedure that follows is typical for electrically fired bombs. The changes for fused bombs are sufficiently obvious and need no comment.

Wireless signals were sent by the *Guide* 60, 30, and 15 seconds before the explosion. Shortly before the firing switch was thrown, the chronographs on the two vessels and the oscillograph on the *Pioneer* were started. At the firing dash observers at the triangulation stations cut in the firing ship, the *Guide*. The oscillograph was stopped after the firing dash recorded, and started just before the arrival of the sound at the hydrophones, the approximate travel time having been known. The arrival of the sound operated the receiving ship *Pioneer's* radio transmitter which was recorded on the *Guide* and also served as a signal for the triangulation observers to cut in the *Pioneer*. No maneuvering of the *Pioneer* occurred from 30 seconds before the explosion until the oscillograph was stopped.

At some distances bomb sounds recorded by the oscillograph were too weak to actuate the *Pioneer's* radio transmitter, giving rise to what are later referred to as "zones of silence." (The transmitter was manually tripped in such cases to signal the triangulation observers.)

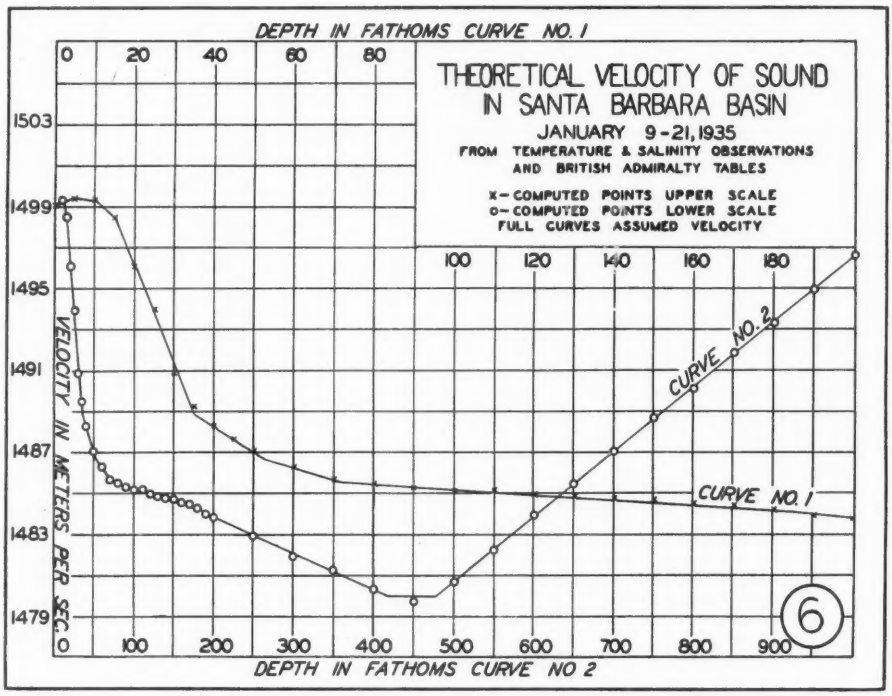


FIG. 6

THEORETICAL VELOCITY-DEPTH DATA

A total of 148 temperatures and 41 salinity observations were taken by the two vessels during the course of the work from which theoretical velocity-depth relations could be computed. The temperature and salinity curves are shown in Figures 4 and 5, the theoretical velocities (computed from the British Admiralty tables)[3] are plotted in Figure 6.

With the velocity-depth relationship of Figure 6 it is apparent that horizontal transmission is theoretically possible only at "velocity inversions," and thus distance limits are imposed beyond which any reflection should not be observed. A ray travelling horizontally at the surface (called a tangent ray) is bent downward by refraction, to reappear at the surface by reflection from the bottom if the velocity at the bottom is less than the surface velocity. The distance between surface grazings defines the limits over which energy reflected once from a (horizontal) bottom is observable. A tangent ray also defines an energy "discontinuity" along which diffraction must occur, extending the horizontal range over which it should be audible. See Figure 24.

DEEP WATER TESTS—NEAR SURFACE BOMBS

Multiple Reflections

Time-distance plots of data obtained in the deep water tests for near surface bombs and hydrophones are shown in Figures 7 and 8. The curves are observational. As for nomenclature, the *P* indicates a compressional wave, *D* a direct path from source to receiver, and *R* reflection. Where numerals follow *PR* the first numeral indicates the number of incidences at the bottom (or grazings), the second numeral the number of incidences at the surface.

In order to obtain a more open time scale, reduced travel time plots are also shown in Figures 10 and 11 in which each travel time is reduced by the quotient *distance in meters* over *1,500*. All impulses can be shown on the reduced plots while only the main events can be shown in Figures 7 and 8.

One fundamental purpose of the experimentation was to establish ray paths. The travel time of $PR1$ should be about half that of $PR2$ for twice the distance, one-third that of $PR3$ for thrice the distance, etc., and the same holds for the reduced travel times. This comparison is shown in Figure 9. The comparison is not carried beyond 30 km for $PR1$ or much beyond 60 km for multiples to avoid serious complications due to diffraction of $PR1$ (See Fig. 24) and decreasing depth of the bottom for the multiples. We consider the display as convincing proof of reflection paths. The curvature of the travel time curves of course shows the same thing.

First Arrivals at Short Distances

The first arrivals at the shorter distances are plotted in Figures 11 and 12. The points in Figure 11 show scattering as expected due to errors in total time

[3] *Tables of the Velocity of Sound, etc.* H. D. 282 Hydrographic Dept. Admiralty (1927).

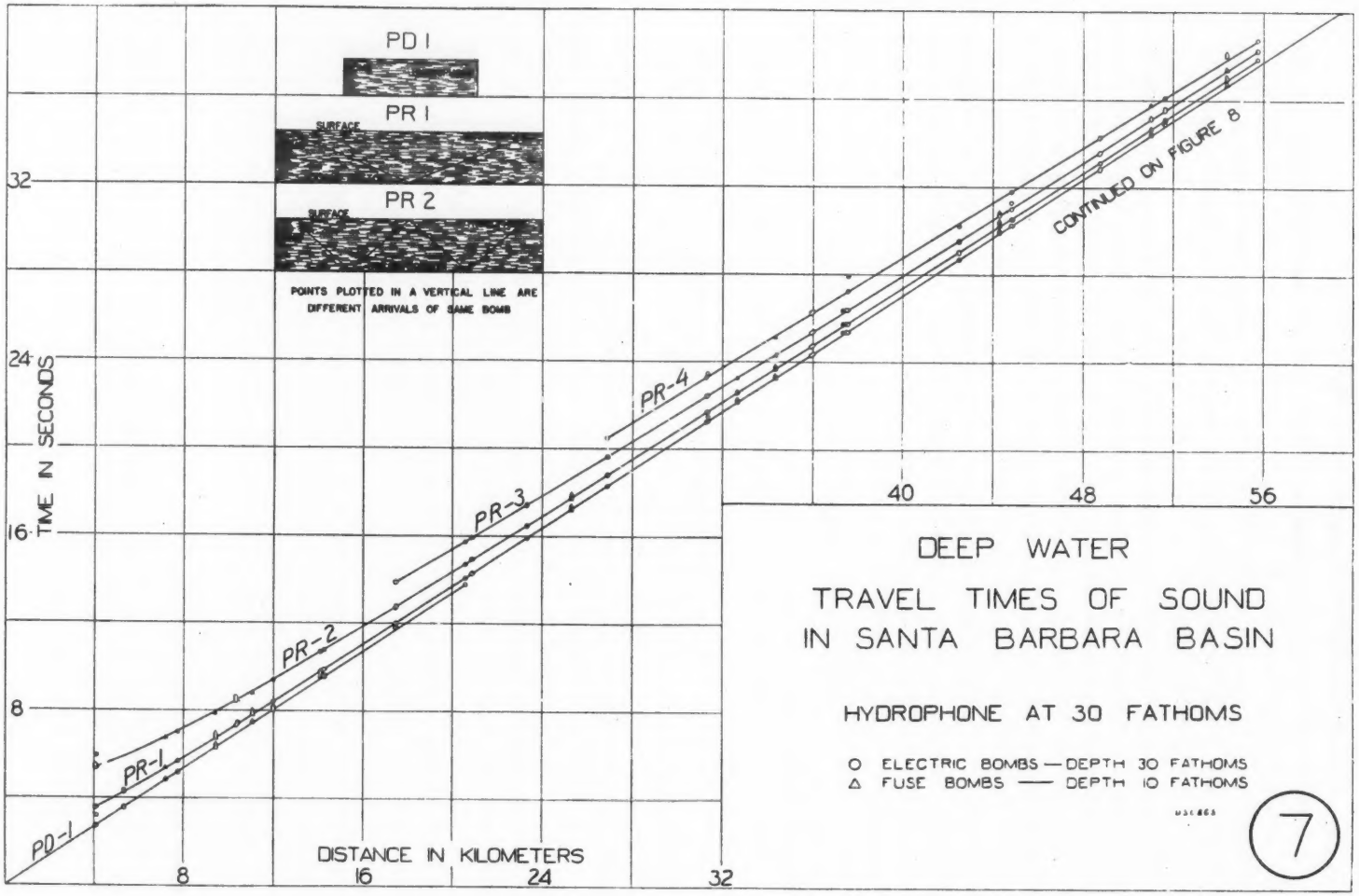

PD 1
PR 1
SURFACE
PR 2
SURFACE
POINTS PLOTTED IN A VERTICAL LINE ARE DIFFERENT ARRIVALS OF SAME BOMB
CONTINUED ON FIGURE 8
PR-4
PR-3
PR-2
PR-1
PD-1
TIME IN SECONDS
8
16
24
32
DISTANCE IN KILOMETERS
8
16
24
32
40
48
56
DEEP WATER
TRAVEL TIMES OF SOUND
IN SANTA BARBARA BASIN
HYDROPHONE AT 30 FATHOMS
O ELECTRIC BOMBS — DEPTH 30 FATHOMS
Δ FUSE BOMBS — DEPTH 10 FATHOMS
7

FIG. 7

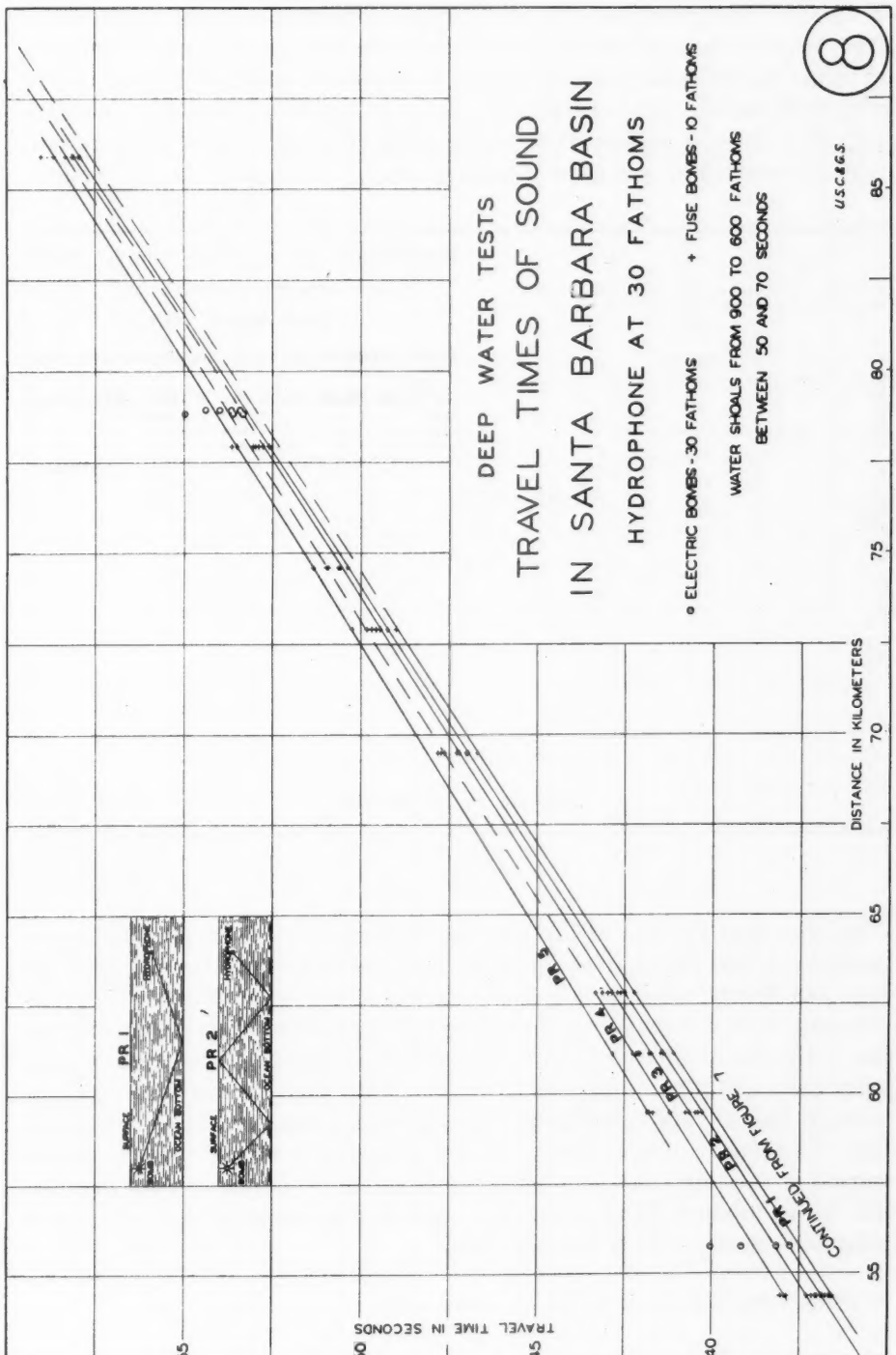

DEEP WATER TESTS
TRAVEL TIMES OF SOUND
IN SANTA BARBARA BASIN
HYDROPHONE AT 30 FATHOMS
• ELECTRIC BOMBS - 30 FATHOMS + FUSE BOMBS - 10 FATHOMS
WATER SHOALS FROM 900 TO 600 FATHOMS
BETWEEN 50 AND 70 SECONDS
USC&GS
8
TRAVEL TIME IN SECONDS
DISTANCE IN KILOMETERS
CONTINUED FROM FIGURE 7
PR 1
PR 2
PR 3
PR 4
PR 5
DB 3
PR 1
SURFACE
OCEAN BOTTOM
HYDROPHONE

FIG. 8

FIG. 7

and distance determinations. As $PR1$ is easily correlatable at the distances involved, errors in time and distance can be suppressed by plotting as in Figure 12. The points on the lower curve of Figure 12 are shown as x's in Figure 11; the points on the middle curve of Figure 12 appear as circles in Figure 11, and on the upper curve as Greek crosses. The validity of the lower two curves of Figure 11 is considered established, and there is excellent reason for drawing the upper curve.

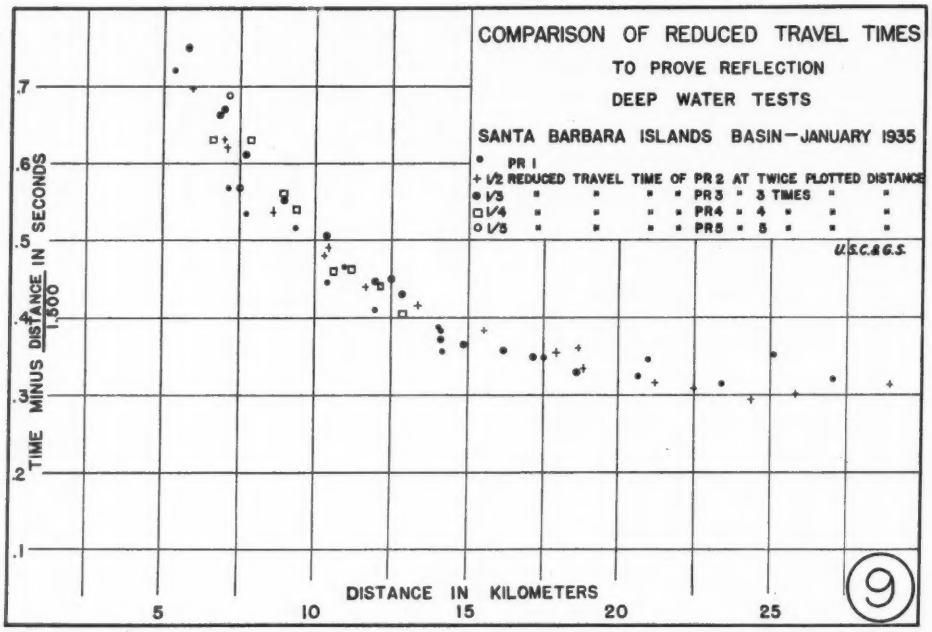


FIG. 9

We note that the two earlier impulses of Figure 11 are on parallel curves. Parallelism in the travel time curves of P waves in earthquakes has been observed and Byerly[4] suggests it is due to change of type upon incidence at a discontinuity. This explanation is of no help in the present instance. The first impulse, $PD1$ was attributed to the displacement of water by the expanding explosive gases and it was suggested the second $PD2$, could be due to the collapse of the gas bubble. The two impulses have about the same maximum amplitude which was thought to be consistent, and a difference in sign of the first motion occurred in the three instances when the direction of motion of both impulses could be determined. The latter is not conclusive evidence in view of the possibility of dispersion effects discussed later.

[4] Byerly, Perry, *Bull. S.S.A.*, Vol. 28, No. 1 (Jan. 1935).

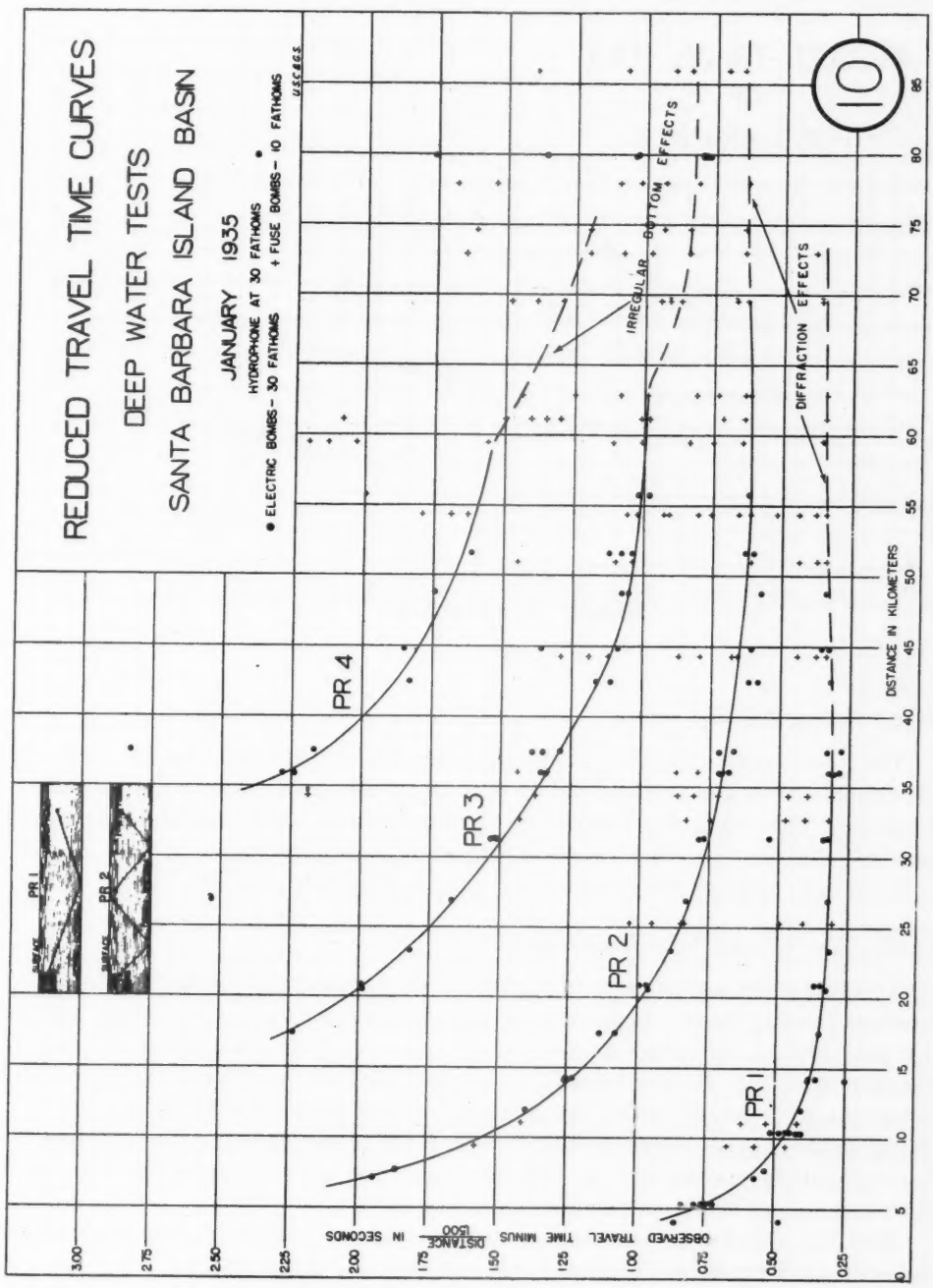

REDUCED TRAVEL TIME CURVES
DEEP WATER TESTS
SANTA BARBARA ISLAND BASIN
JANUARY 1935
HYDROPHONE AT 30 FATHOMS
● ELECTRIC BOMBS - 30 FATHOMS + FUSE BOMBS - 10 FATHOMS
USC&GS
PR 1
PR 2
PR 3
PR 4
IRREGULAR BOTTOM EFFECTS
DIFFRACTION EFFECTS
OBSERVED TRAVEL TIME MINUS DISTANCE/1500 IN SECONDS
DISTANCE IN KILOMETERS
10

FIG. 10

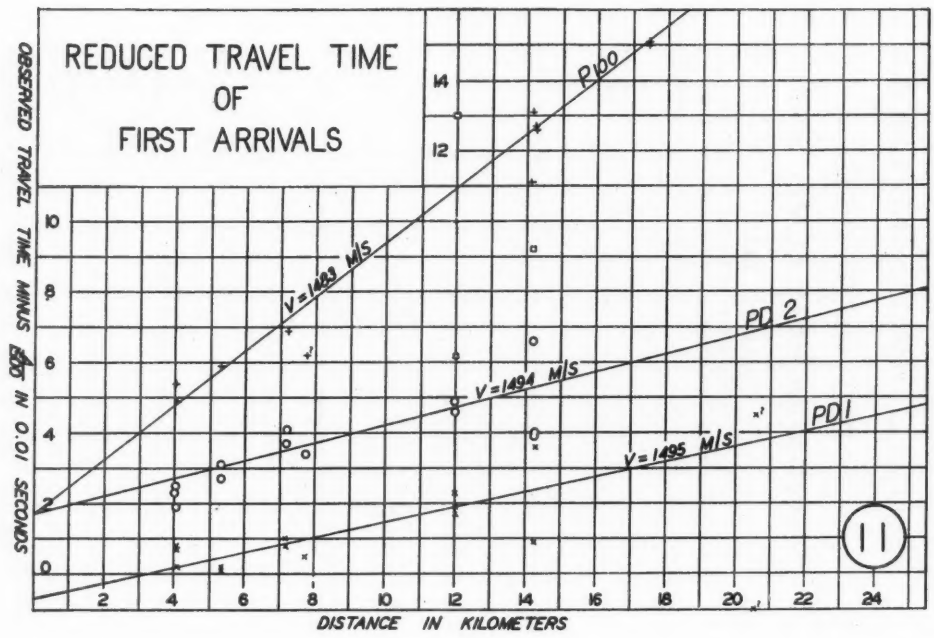


FIG. 11

High Velocity Near the Source

The lower curve does not pass through the origin. This could be due to observational errors, but is likely due in part to an abnormally high velocity near the source. This effect was reported by Threlfall and Adair.[5] Since the path associated with the two lower curves of Figure 11 is probably more or less direct from bomb to hydrophone, these arrivals are labelled *PD*1 and *PD*2.

Travel Along Second Order Discontinuity

To explain the upper curve of Figure 11 travel along the 100 fathom (near) constant velocity layer was postulated. The apparent velocity is consistent with this idea, and an emergence angle of about 30° would give the appropriate zero distance intercept. It is extremely interesting that we here have evidence of diffraction at a second order discontinuity—a constant velocity layer with a change in the rate of change of velocity with depth at its upper and lower surface. No explanation was offered as to why only one *P*100 was observed when the two *PD*'s have about the same maximum amplitudes.

With bomb and hydrophone at 100 fathoms, an event with an average velocity of about 1,483 m/sec was observed which strengthens the evidence for transmission along this layer.

[5] *Proceedings Royal Society* 46 (1889), p. 496.

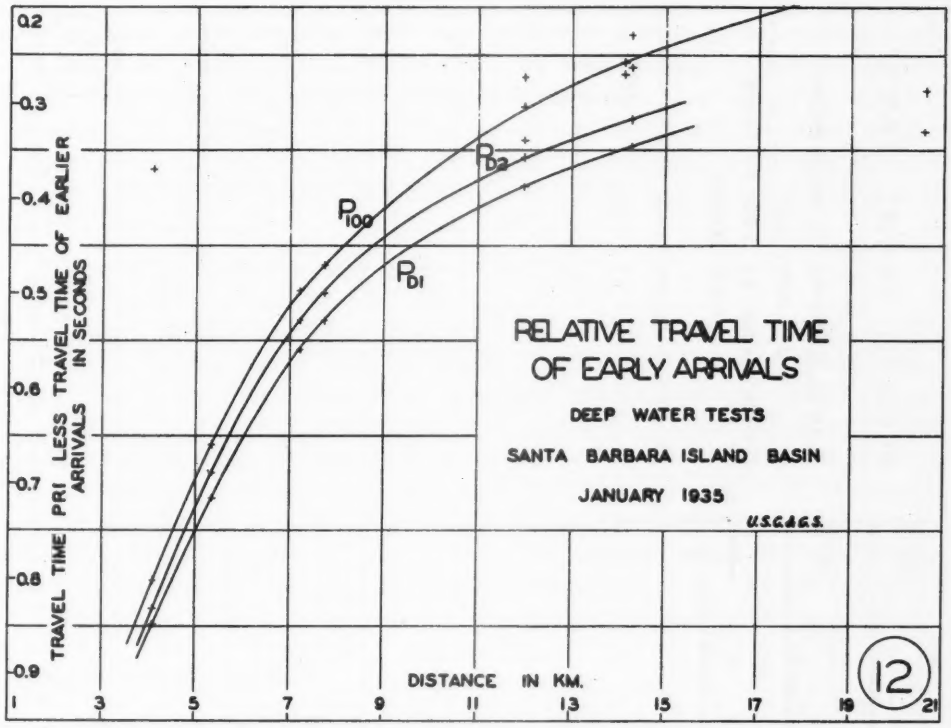


FIG. 12

Velocity in the Ocean Floor

A striking feature of the travel time curves of Figure 10 is the absence of multiple reflections at the shorter distances. Very often the oscillograph was stopped too early to record the later reflections; however, three records at distances of 20.9 to 23.3 km show no trace of PR_4 at the expected time. At 26.9 km one record shows no evidence of PR_4, while on another it was recorded feebly. All were electrically fired four-ounce bombs. At distances in excess of 27 km, PR_4 was always recorded when the records were long enough. PR_5 was not well recorded at any distance, but the shortest distance at which it appeared was 37.5 km. Associating the minimum distance at which PR_4 was observed with the critical angle for total reflection gives a maximum velocity of 1,580 m/sec in the material underlying the water. Velocities of this order have been reported for water-soaked sand.

Limited Range of PR1

More important (than the absence of multiple reflections at the shorter distances) from the standpoint of RAR was the failure of PR_1 to record satisfactorily at the greater distances due to ray curvature. PR_1 was observed on the

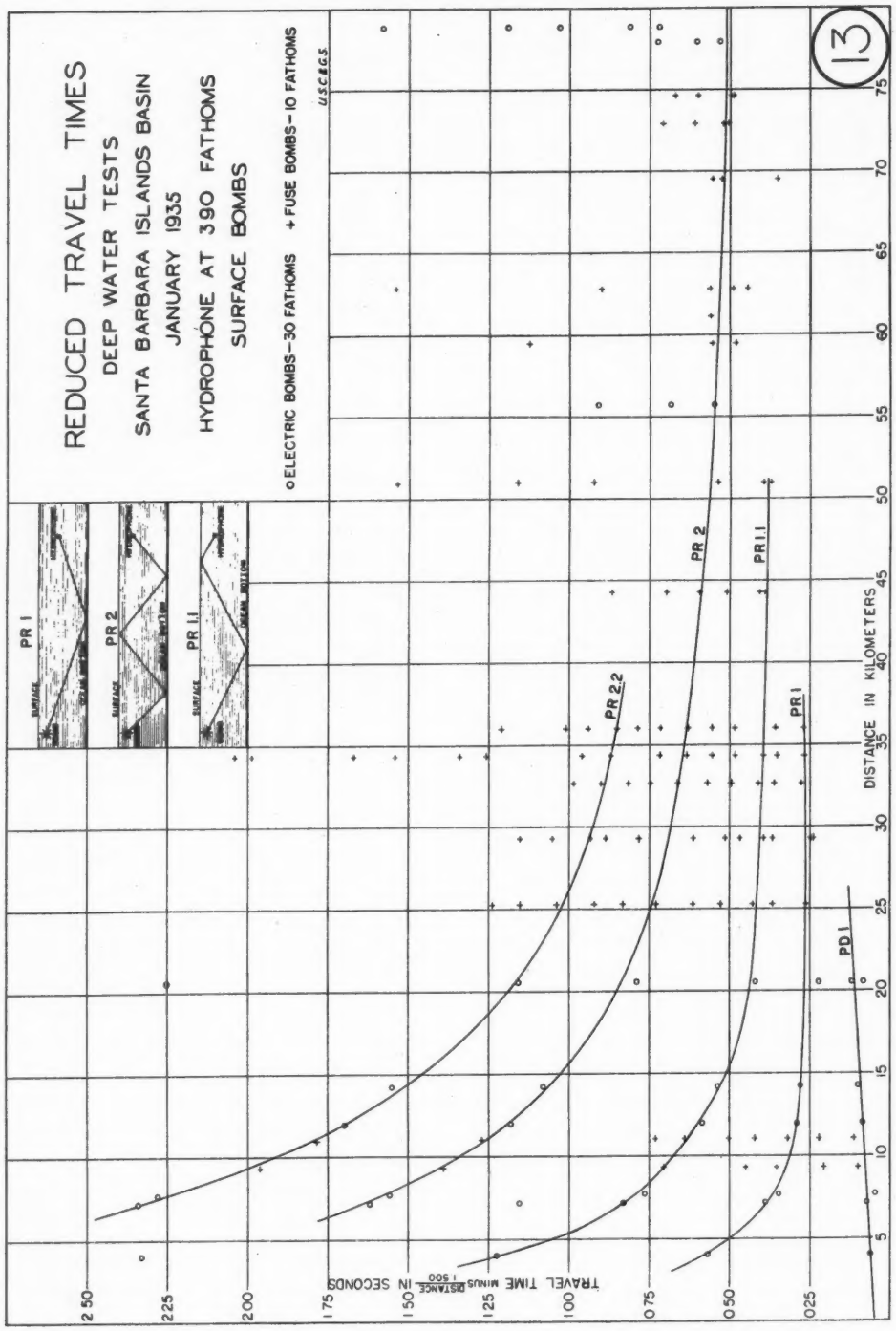

REDUCED TRAVEL TIMES
DEEP WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
HYDROPHONE AT 390 FATHOMS
SURFACE BOMBS
o ELECTRIC BOMBS—30 FATHOMS + FUSE BOMBS—10 FATHOMS
USC&GS
13
PR 1
PR 2
PR 1.1
PR 2.2
PR 2
PR 1.1
PR 1
PD 1
TRAVEL TIME MINUS DISTANCE/1500 IN SECONDS
DISTANCE IN KILOMETERS
250
225
200
175
150
125
100
075
050
025
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75

FIG. 13

oscillograph as far as 52 km with 4-ounce bombs, and to 73 km with 8-ounce bombs. For both bomb sizes *PR*1 became very weak at the greater distances, and its duration on the oscillograms reduced from tenths of a second to about a hundredth of a second. The greatest distance at which *PR*1 recorded on the chronograph was 45 km and 55 km respectively. The distance limitation imposed by ray curvature and mentioned under the discussion of theoretical velocities is clearly demonstrated.

Multiple Impulses

There is a clearly marked tendency for the events from the one-half pint bombs fired at 10 fathoms to occur in groups of three, the intervals being about 0.10 seconds. See *PR*1 Figure 10 at distances of 9, 11, 25, 33, and 34 km, *PR*3 at 54 km, etc. An event was also frequently present about 0.03 second after the first of the group of three. The time intervals appear independent of distance, number of reflections that have occurred, and depth of receiver. (See Fig. 13.) The source of the multiplicity is therefore in the explosion. The 0.03 second interval was thought to be due to the collapse of the gas bubble mentioned elsewhere, but no mechanism for the 0.10 second interval was suggested.

The multiplicity was observed to a lesser extent for the smaller bombs.

Data at Deep Hydrophones

Reduced travel time data for near-surface bomb sounds received at a hydrophone at a depth of 390 fathoms are shown in Figure 13. *PD*1 is observed to a greater distance than at the near-surface hydrophone as would be expected. Both *PR*1 and *PR*1.1 recorded to a lesser distance than did *PR*1 at the near surface. This is also as would be expected.

BOMBS FIRED AT DEPTH

Comparison with Near-Surface Data

Time-distance data for deep bombs with a hydrophone at the same depth are shown in Figure 14. The full lines labelled *PR*1.1, *PR*2.2, *PR*3.3, and *PR*4.4 are taken from Figure 10 where they are labelled *PR*1, *PR*2, *PR*3, and *PR*4 respectively. It is evident that the travel time of *PRn.n* with bomb and hydrophone at the same depth should be independent of that depth and equal to that for *PRn* with bomb and hydrophone at the surface, assuming a level bottom. The bottom was level to a first approximation only.

Path of First Arrivals

The first arrivals at the deep hydrophone can be interpreted as having traveled in practically a straight line at an average velocity of around 1,483 meters per second, a satisfactory check of the theoretical velocity as departures of 50 meters (0.05 seconds) in the position of a deep hydrophone can readily arise

due to departure from the vertical of the supporting cable. Reasonable alternative explanations of the first arrival times are possible. The first arrival at 56 km may be *PR*1.2, at 43 km and 36 km *PR*1.1, and at 6 and 8 km *PRO*.1; the one at 26 km may be *PR*1.0 diffracted. To establish experimentally the paths beyond doubt would require closer spacing of observational points and good amplitude control to permit resolution of closely spaced events. However, there

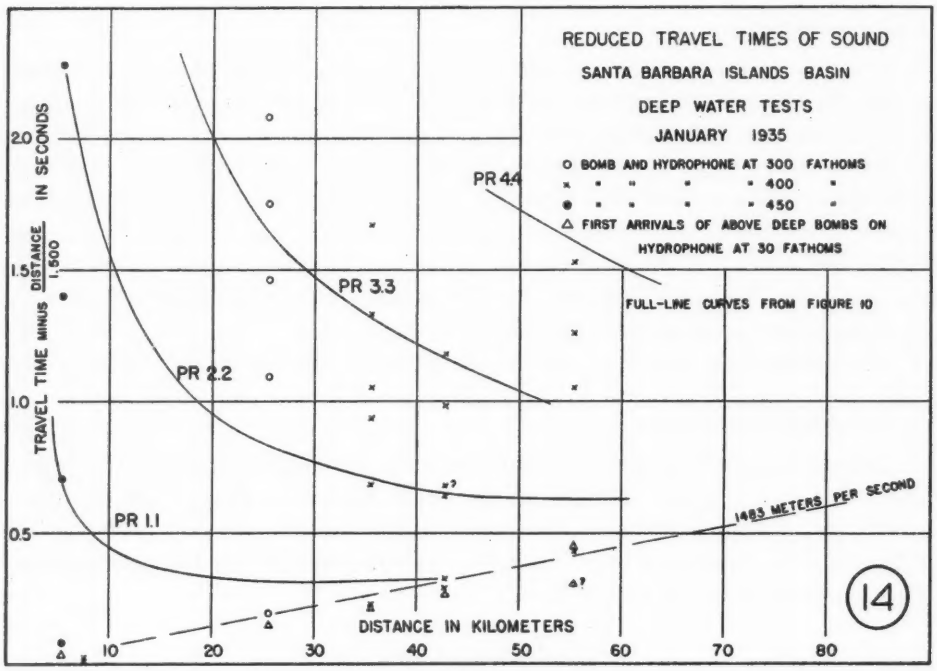


FIG. 14

is very good *a priori* reason to expect the transmission of energy along the "constant velocity" layer at about 400 fathoms.

In discussing this phenomenon the report of the 1933 work stated, "It should be noted that if the source is in, say the 450 fathom constant velocity layer, direct paths to subsurface points at great distance are theoretically possible. These paths are somewhat sinuous."

In the 1936 report[2] the following statement was made, "A more detailed study of the properties of constant velocity layers may be of value for special problems in RAR and coast defense."

The later arrivals of Figure 14 are the expected reflections and nothing unusual appears that warrants comment.

Check of Theoretical Velocities

With the possible exception of the velocity of about 100 fathoms, the data yield only the average vertical velocity between certain depths. (The instantaneous velocity of *PD*-1 and *PD*-2 cannot be attributed to any one depth because of the uncertainty regarding the path.)

During the *Guide's* fuse-bomb run, a sounding line was run taking soundings every quarter mile (Fig. 2). All the deep water tests were carried out near this line or its extension. The slope of the bottom is quite steep until a depth of 1,020 fathoms is attained, after which it is extremely gentle for some distance. The steep slope ends at about five km from the average position of the *Pioneer*. There is therefore little error in taking the depth of bottom from the profile at distances greater than six or seven km.

The average velocities from a depth of 30 fathoms to the bottom were computed from the travel time of *PR*-1 taking the depths from the profile for the bombs when it was certain that the point of reflection was on the level part of the profile. Bombs Nos. 424, 425, 426, at 10.4 km were included since the position of the *Pioneer* for these bombs was about a mile south of the average position assuring the reflection from the level part. Only electric bombs at distances less than 21 km were used so that it can be assumed reflection from the bottom actually occurred, and the ray paths approximate straight lines. The bombs and hydrophones were at a depth of 30 fathoms.

The average experimental velocities from 30 fathoms to 1,020 fathoms were obtained as follows:

Bomb Number	Average Velocity	Residuals
424	1,491 m/sec	−2.8
425	1,491	−2.8
426	(1,500) Rejected	
427	1,487	+1.2
428	1,486	+2.2
429	1,488	+0.2
430	1,487	+1.2
431	1,485	+3.2
432	(1,482) Rejected	
542	1,491	−2.8
543	1,489	−0.8
544	1,490	−1.8
546	1,491	−2.8
547	1,487	+1.2
548	1,487	+1.2
549	1,488	+0.2
550	1,486	+2.2
	Mean 1,488.2	

Mean Experimental Average Velocity between 30 and 1,020 fathoms 1,488 m/sec.
Mean Theoretical Average Velocity between 30 and 1,020 fathoms 1,486 m/sec. (computed from British Admiralty Tables).

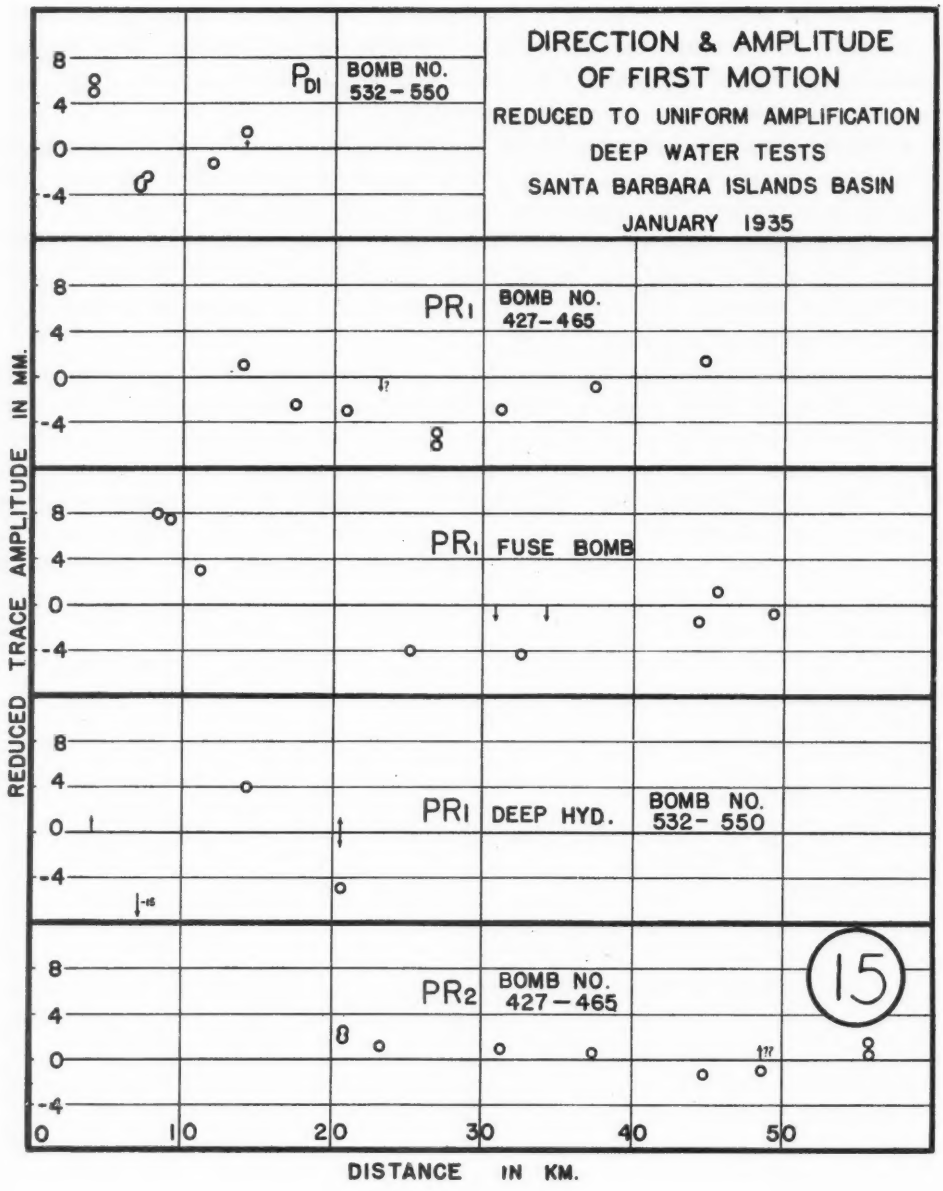

DIRECTION & AMPLITUDE
OF FIRST MOTION
REDUCED TO UNIFORM AMPLIFICATION
DEEP WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
PD1
BOMB NO. 532-550
PR1
BOMB NO. 427-465
PR1
FUSE BOMB
PR1
DEEP HYD.
BOMB NO. 532-550
PR2
BOMB NO. 427-465
15
REDUCED TRACE AMPLITUDE IN MM.
8
4
0
-4
0
10
20
30
40
50
DISTANCE IN KM.

FIG. 15

The agreement between the experimental and theoretical values is remarkable. Curiously enough, if one considers the apparent high speed near the source noted elsewhere, the agreement is exact to the nearest m/sec.

DIRECTION AND AMPLITUDE OF FIRST MOTION

Limitations of Data

Usually the direction and amplitude of first motion of individual events could not be determined either because of concomitant trace motion or record faintness resulting from high amplitudes. The relation between first motion and water motion is not known since it was not certain that the electrical connections were always made in the same way. In Figure 15 only those measurements are grouped together for which it is quite certain no change in connections was made. Graphs for different bomb series cannot be compared for actual direction of motion.

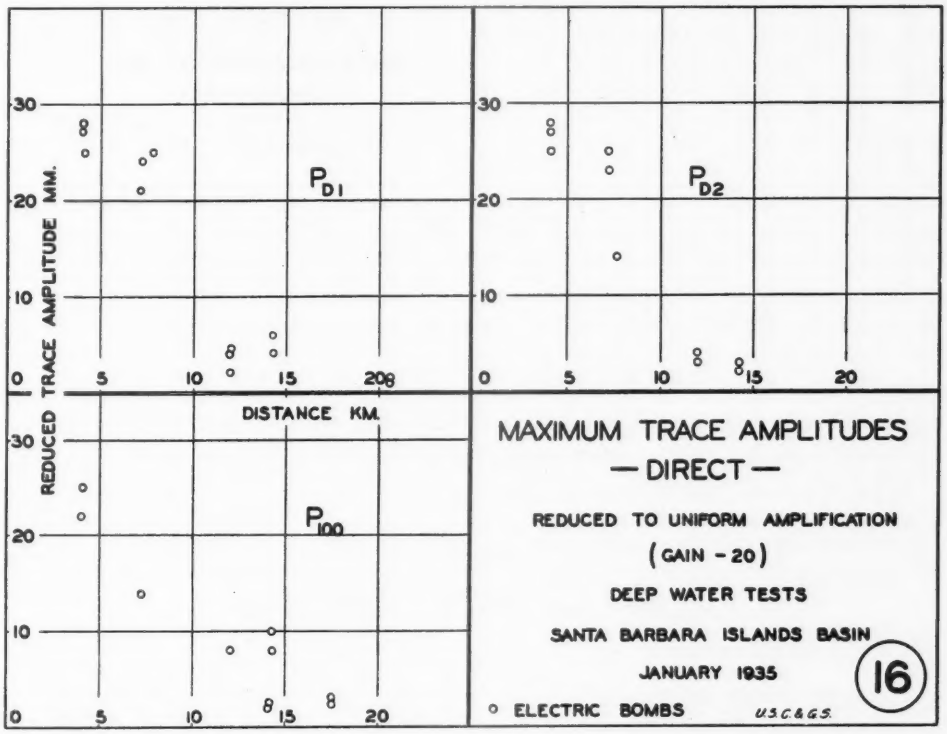


FIG. 16

Evidence of Dispersion

For a given ray path, the direction of first observed motion changes with distance. This is contrary to views that have been expressed in this connection.[6]

[6] See for example Jeffreys, H., *The Earth*, p. 94, Cambridge University Press (1929).

The changing front could result either from dispersion or the loss of complete half waves. If due to the latter, the amplitude distance curve should be discontinuous with each half cycle of a wave showing a maximum when that half cycle appears as the first arrival. As the observed curves appear continuous with the maximum midway between the zero amplitude transits, they were considered as very strong evidence for dispersion. (Worzel and Ewing[7] have since reported other evidence of dispersion in waterborne sound.)

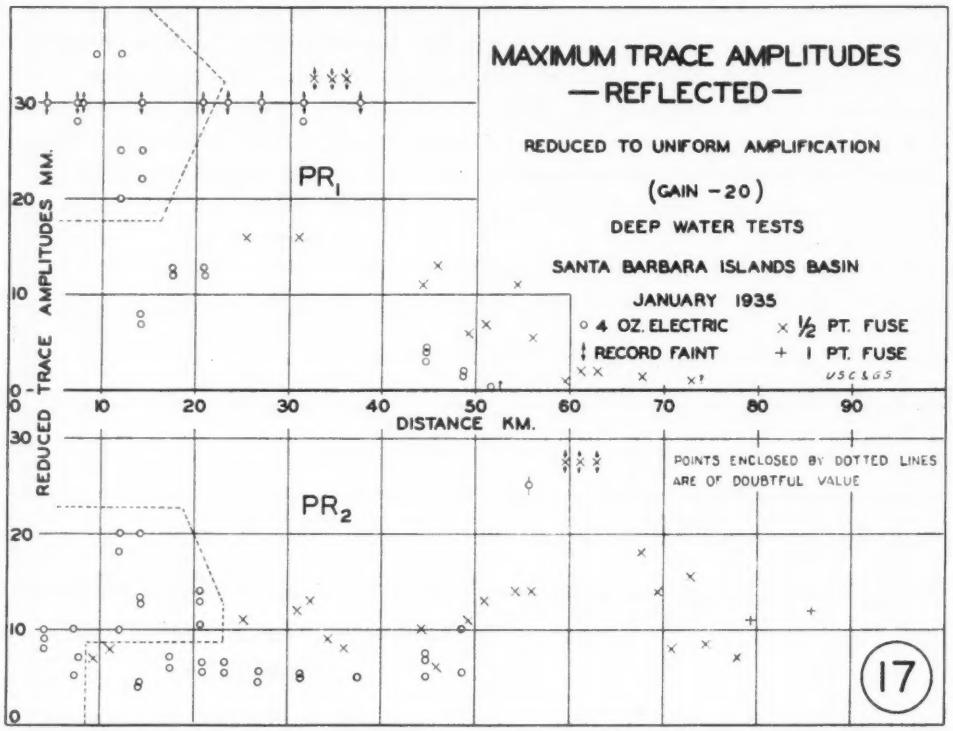


FIG. 17

MAXIMUM AMPLITUDES IN VARIOUS PHASES

Nature of the Observations

The maximum trace amplitude of an event was taken as the maximum occurring within the first 0.1 sec or less of that event. It was often impossible to determine the maximum amplitude, and this is indicated by double-headed arrows on the plots; usually, but not always, this indicates high amplitude. (See Figs. 16, 17, 18.)

The amplitudes for bombs 532–550 inclusive were considerably higher than those found on other days for the same size bombs. In Figure 17 these observa-

[7] Worzel and Ewing, *G. S. A. Memoir No. 27* (1948).

tions are set apart by dashed lines. Leaving this as unexplained, data from the two principal bomb sizes show the same characteristics with distance.

"Direct" Wave Amplitudes

Other than the surprisingly high amplitudes of $P100$ relative to $PD1$ and $PD2$, the direct (near surface) waves show nothing unusual. If the suggested path of $P100$ is correct one would expect an amplitude small in comparison with that of $PD1$ particularly at short distances.

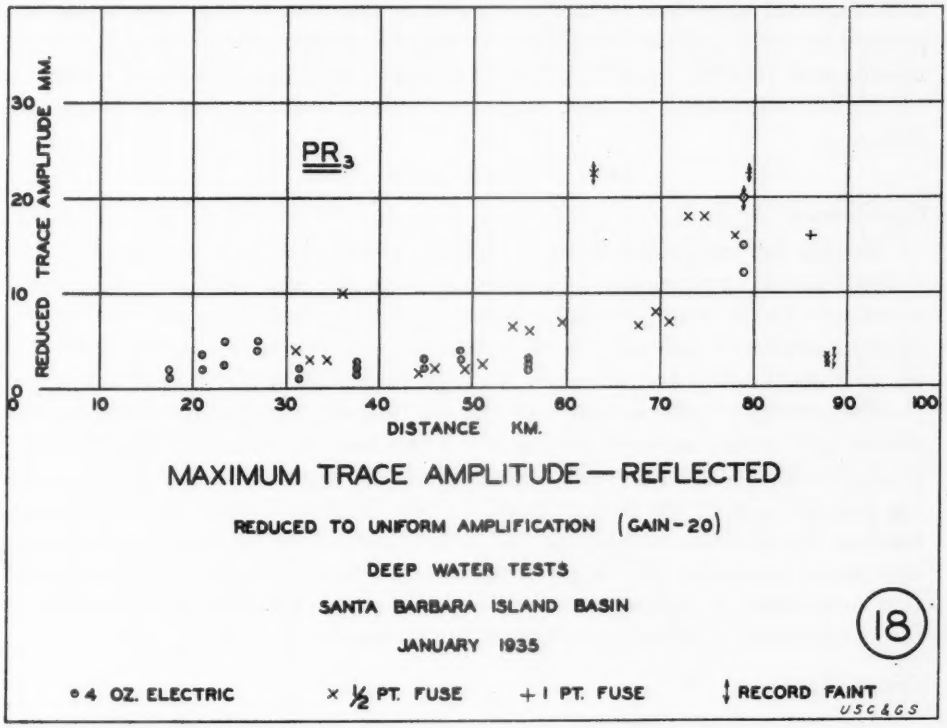


FIG. 18

Reflection Amplitudes

Referring to Figures 17 and 18, $PR1$ shows a maximum at about 35 km, $PR2$ at about 60 km, and $PR3$ at about 80 km. The maxima could possibly result from directional effects as the ray paths become horizontal at certain distances. The hydrophones supposedly responded to pressure variations, but this was not verified experimentally. There was some reason to believe that the motion of the hydrophone as a whole, as well as pressure induced diaphragm motion, would excite the Utah unit so directional properties may have been present. However, energy peaks would be expected from the nature of the velocity-depth function.

Using Slichter's[8] criteria (his case 1, p. 281) we find that the conditions for a travel-time curve with a reversed segment and its resulting focusing effect are met. Amplitude peaks due to this cause should broaden with each reflection, but the observations do not prove this. Unfortunately no fuse bomb data were obtained between 36 and 44 km to better delineate the *PR*1 maximum.

Diffraction Effects

It is reasonable to relate the *PR*1 data beyond the amplitude drop at about 40 km to diffraction effects. The extension of the range of the diffraction interval with increased bomb-size is very noticeable in the case of *PR*1. The diffraction interval for *PR*1 is about 30 km and yet the near-surface direct waves (for small bombs) were received to only 20 km. This suggests a preponderance of energy in the higher frequencies at short distances, and in lower frequencies at greater distances.

DEEP TO SHOAL WATER TESTS

Conditions of the Tests

The sea bottom profile of the experimental area is shown in Figure 3. The vertical scale is exaggerated, the average slope at the steep portion actually being about 10°. As the emergence angle is increased by an amount equal to twice the angle of slope upon reflection from the bottom, the conditions are not favorable for shoreward sound transmission. At large emergence angles 90 percent of the incident energy is transmitted into the sea bottom, and the small amount reflected may return seaward after a few reflections. As seen from Figure 3, the average bottom slope happened to roughly parallel the tangent ray while beyond the foot of the slope the bottom is quite level. With this combination of circumstances, the presence of the slope had little effect on the travel time of the first arrivals at distances involving a tangent ray. From the foregoing it is evident that near-shore hydrophones should be placed out as far as possible, at least as far as the head of the steepest slope of the bottom.

Direct Wave

The travel time curves are shown in Figures 19, 20, 21, and 22. The direct impulse was not observed beyond a distance of 8½ km. It shows an instantaneous velocity of 1,500 m/sec and a negative time intercept. This velocity is 5 m/sec higher than observed in the deep water tests, undoubtedly because near-surface temperatures were slightly higher inshore than offshore. The intercept below the origin was also observed in the deep water tests and could be due to a high velocity near the source.

Reflected Waves

From about 13 to 20 km the arriving sounds had too little energy to operate the radio transmitter but did record faintly on the oscillograms. (See also Fig.

[8] Slichter, L., *Physics*, Vol 3, No. 6 (Dec. 1932).

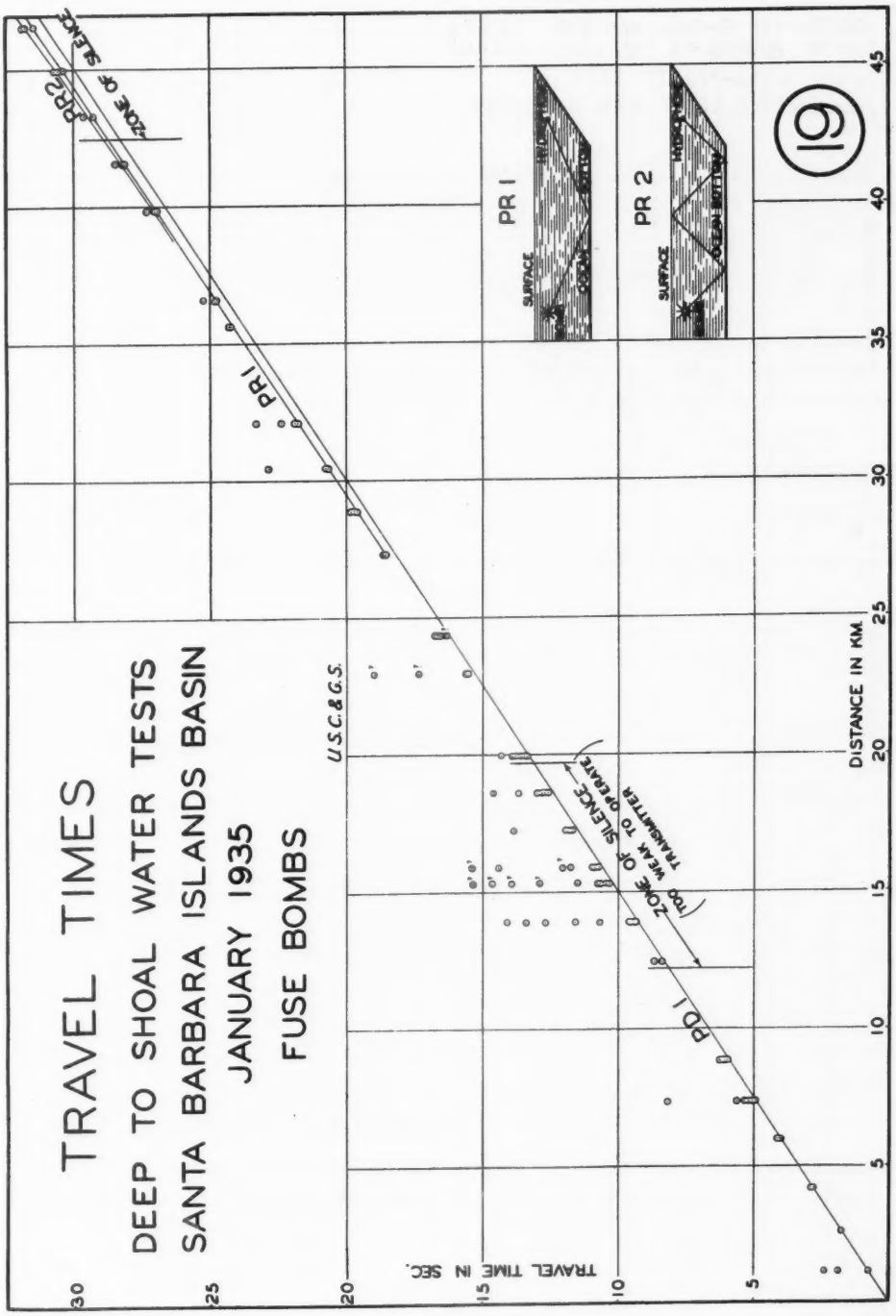

TRAVEL TIMES
DEEP TO SHOAL WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
FUSE BOMBS
U.S.C.&G.S.
TRAVEL TIME IN SEC.
DISTANCE IN KM.
PD1
PD2
PR1
ZONE OF SILENCE
TOO WEAK TO OPERATE
TRANSMITTER
PR 1
PR 2
SURFACE
19

FIG. 19

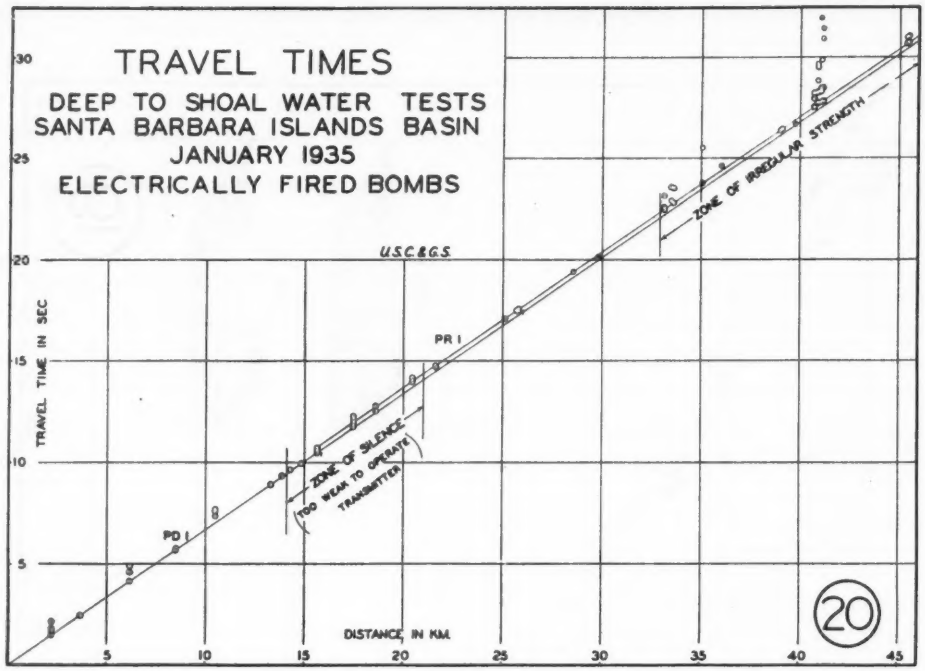

TRAVEL TIMES
DEEP TO SHOAL WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
ELECTRICALLY FIRED BOMBS
U.S.C.&G.S.
TRAVEL TIME IN SEC
DISTANCE IN KM.
PR I
PD I
ZONE OF SILENCE
(TOO WEAK TO OPERATE TRANSMITTER)
ZONE OF IRREGULAR STRENGTH
20

FIG. 20

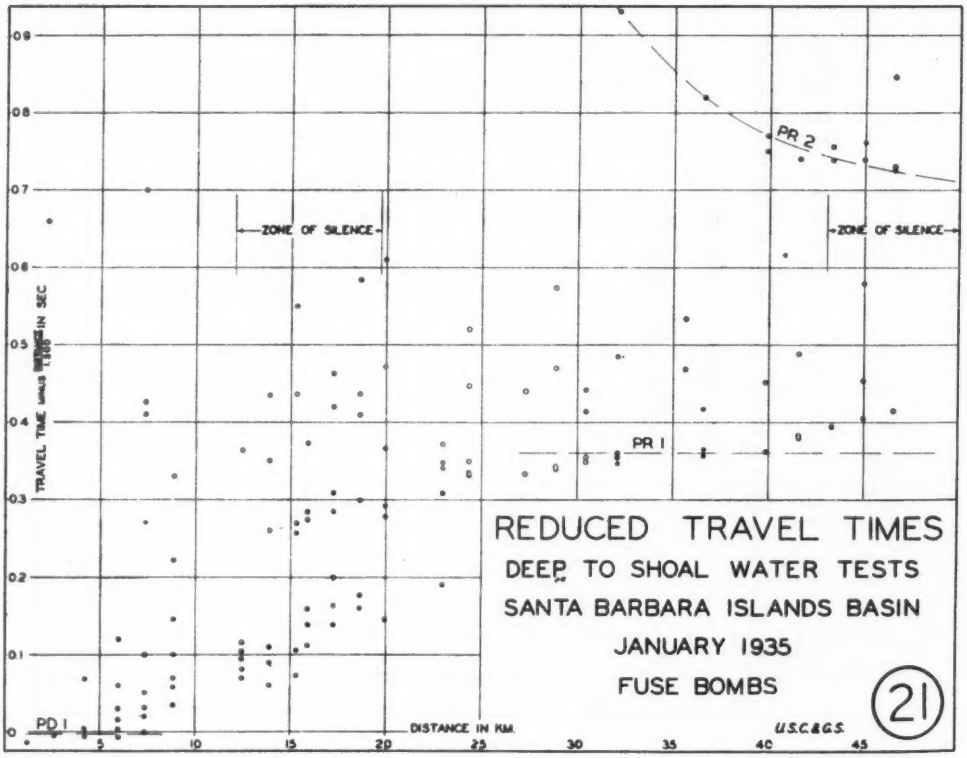

PR 2
PR I
PD I
ZONE OF SILENCE
ZONE OF SILENCE
TRAVEL TIME MINUS DISTANCE/1.800 IN SEC
DISTANCE IN KM.
U.S.C.&G.S.
REDUCED TRAVEL TIMES
DEEP TO SHOAL WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
FUSE BOMBS
21

FIG. 21

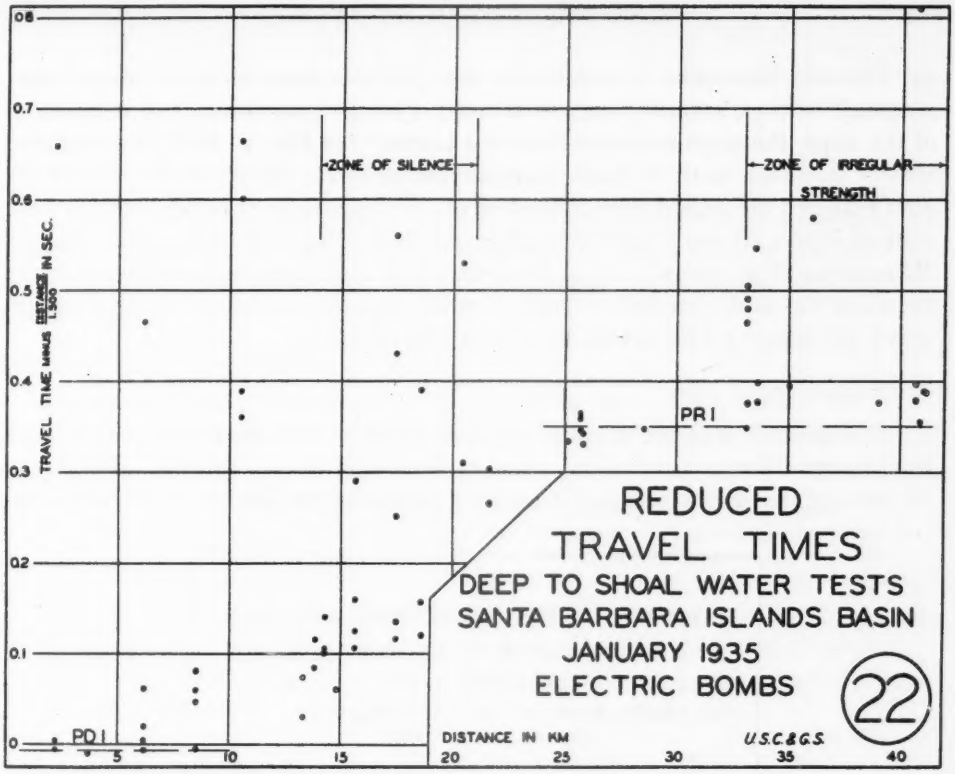

ZONE OF SILENCE
ZONE OF IRREGULAR STRENGTH
PR I
PD I
TRAVEL TIME MINUS DISTANCE/1.500 IN SEC.
DISTANCE IN KM
REDUCED
TRAVEL TIMES
DEEP TO SHOAL WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
ELECTRIC BOMBS
22
U.S.C.&G.S.

FIG. 22

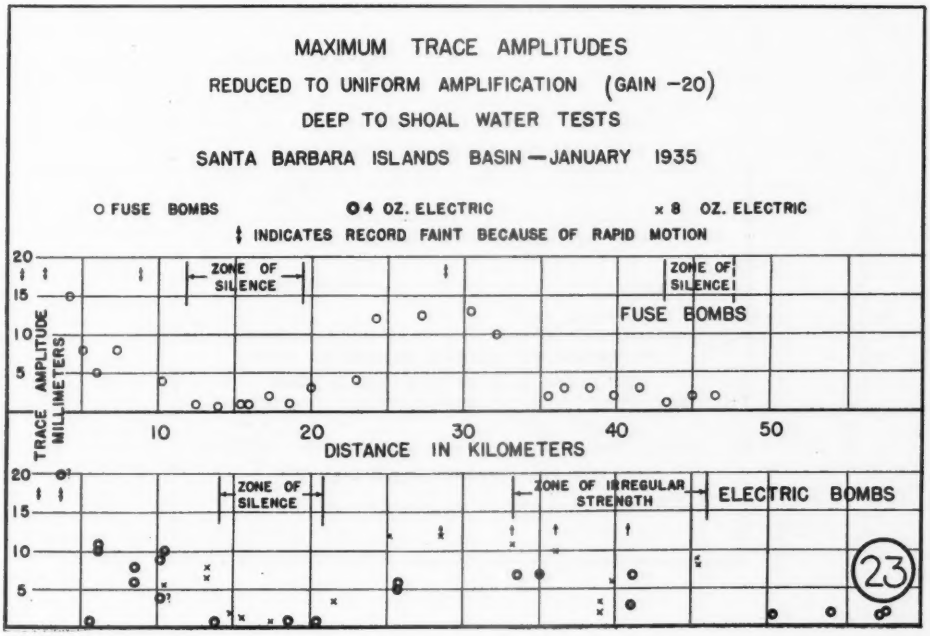

MAXIMUM TRACE AMPLITUDES
REDUCED TO UNIFORM AMPLIFICATION (GAIN −20)
DEEP TO SHOAL WATER TESTS
SANTA BARBARA ISLANDS BASIN — JANUARY 1935
○ FUSE BOMBS
● 4 OZ. ELECTRIC
× 8 OZ. ELECTRIC
INDICATES RECORD FAINT BECAUSE OF RAPID MOTION
ZONE OF SILENCE
FUSE BOMBS
TRACE AMPLITUDE MILLIMETERS
DISTANCE IN KILOMETERS
ZONE OF IRREGULAR STRENGTH
ELECTRIC BOMBS
23

FIG. 23

23) This was the region in which only multiple reflections from the slope were recorded. As the distance is reached at which a tangent ray is reflected at the foot of the slope, the slope no longer acts as a barrier (See Fig. 3), and the sound intensity increases. As the distance increases further, PR_1 diffracted dies out before PR_2 reflected the second time at the foot of the slope comes through, and another zone of silence or low intensity is observed at about 42 km. The points on the PR_2 curves (Figs. 19 and 21) are not true PR_2's in that multiple reflection from the slope was undoubtedly involved; bombing was not carried to the distance at which the tangent PR_2 should have been observed.

Anomalous Travel Time

At a distance of about 35 km both the fuse and the electric bombs (which were fired under different conditions), came in from 0.05 to 0.22 seconds later (Figs. 21 and 22), no doubt because of an irregularity in the bottom. It is fortunate

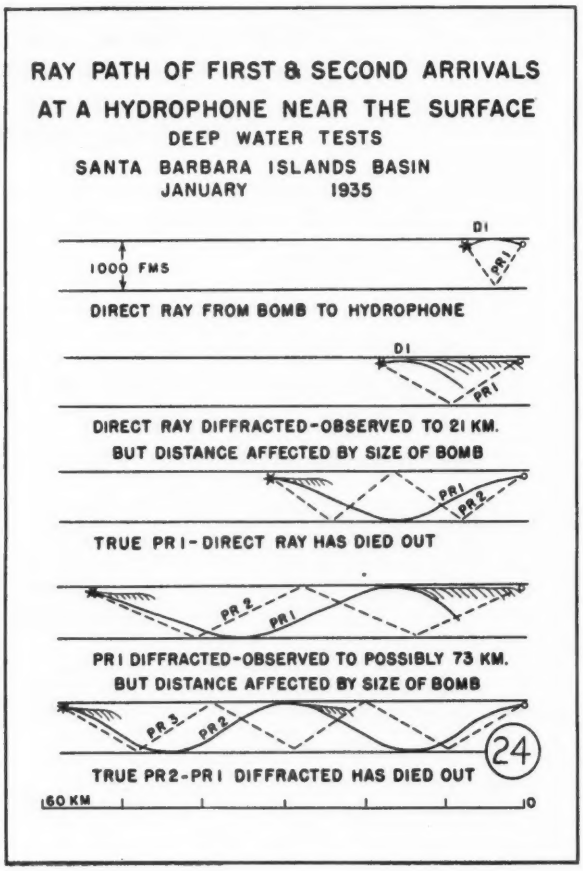


FIG. 24

that this observation is so clearly substantiated as it illustrates sharply the limitations in the accuracy of radio acoustic ranging under the conditions involved.

OBSERVED FREQUENCIES

The hydrophones comprised a complex vibrating system with a number of inherent natural frequencies which were not determined. Damping was poor so it was probable that the several inherent frequencies would be predominant on the records.

Major Frequencies Recorded

The major frequencies present in each impulse were recorded, but no effort was made to evaluate their relative durations. Ordinarily only one occurrence

TABLE I

RELATIVE DISTRIBUTION OF MAJOR FREQUENCIES

Deep Water Tests		Frequencies	200	450	900
Santa Barbara Ids. Basin Electrically fired bombs at 30 fathoms; Aluminum Pot Hydrophone at 30 fathoms	Travel time	0–15 sec	1	0.2	7.4
		15–30 sec	1	1.2	3.3
		over 30 sec	1	0.2	1.3
Deep Water Tests					
Santa Barbara Ids. Basin ½ pint Fuse Bombs; Aluminum Pot Hydrophone at 30 fathoms.	Travel time	0–20 sec	1	0.5	3.4
		over 20 sec	1	0.1	2.0
Deep to Shoal Water Tests		Frequencies	200 to 600 inc.		over 600
Santa Barbara Ids. Basin Electrically Fired Bombs at 30 fathoms; Aluminum Pot Hydrophone about 10 fathoms	Travel time	0–15 sec	1		0.4
		over 15 sec	1		0.1
Deep to Shoal Water Tests		Frequencies	300 to 600 inc.		over 600
Santa Barbara Ids. Basin ½ pint fuse bombs; Aluminum Pot Hydrophone at about 10 fathoms	Travel time	0–15 sec	1		0.3
		over 15 sec	1		0.4
Deep to Shoal Water Tests		Frequencies	100	500	950
Laguna Beach ½ pint fuse bombs; Kettle Drum Hydrophone at about 10 fathoms	Travel time	0–12 sec	1	1.3	1.6
		12–25 sec	1	1.3	0.1
		over 25 sec	1	0.6	0
Deep to Shoal Water Tests		Frequencies	100	450	950
Laguna Beach Electrically Fired Bombs at 30 fathoms; Kettle Drum Hydrophone at about 10 fathoms	Travel time	0–10 sec	1	1.6	2.0
		10–20 sec	1	0.7	0.2
		over 20 sec	1	0.7	0.0

per frequency was recorded per impulse. These frequency of occurrence statistics show maxima at three frequency ranges; namely, 200–250, 450–500, and 900 cps—a fundamental and the first and second harmonics.

A few supplementary records were obtained with a Rochelle salt crystal hydrophone which should provide rather uniform response over the frequency range observed. Records obtained in shallow water at ten miles showed frequencies of from 205 to 260 cps with 220 being the most prominent. As strays of 1,900 cps were present throughout the records, it seems likely that no considerable percentage of energy was present in the range from 260 to 1,900 cps. (Ewing[9] has reported water wave frequencies of 200–250 cps.)

The statistics are segregated into groups according to travel time in Table 1.

The relative incidence of the higher frequencies lessened with distance as would be expected.

There was a tendency for the higher frequencies to persist to somewhat greater distances with increasing bomb size. Pint-sized bombs still gave rise to a rather high percentage of high frequencies even at travel times of 60 seconds, particularly in the first arrivals. The high frequencies were present in the first arrivals in practically all cases in the deep water tests. This was not the case in the deep to shoal water tests with sounds originating in deep water and being received at hydrophones in shallow water.

SUMMARY

Ray paths for sound in deep sea water were established and found to generally correspond to those expected from theory.

In 1,000 fathoms of water, with bomb and hydrophone at a depth of 30 fathoms, sound traveled direct from bomb to hydrophone for a maximum observed distance about 21 km. Diffraction effects were important beyond eight kilometers.

Some energy from bombs fired at a depth of 30 fathoms traveled along a narrow (nearly) constant velocity layer at a depth of 100 fathoms and reached a near-surface hydrophone at distances up to 17½ km. A similar wave from near-surface bombs along the 400 fathom velocity inversion was not observed at a near-surface hydrophone. With bomb and hydrophone at 100 fathoms a wave that apparently traveled along the 100 fathom layer was observed at 26½ km. The first arrivals at a hydrophone at a depth of 400 fathoms from bombs at the same depth may have traveled along the 400 fathom layer as far as 56 km (the maximum distance tried), but alternate explanations also satisfy these data.

Single and multiple reflections were observed. With a fairly uniform bottom at about 1,000 fathoms sound reflected once from the bottom was observed from near-surface bombs to near-surface hydrophone at a maximum distance of 73 km, but the last 35 or 40 km of travel depended on diffraction.

[9] Ewing, M., *Field Engineers Bulletin*, U.S.C.G.S. No. 10 (Dec. 1936), 65.

The mean velocity between 30 and 1,020 fathoms obtained experimentally agreed within a few meters per second with the theoretical. The instantaneous velocity of the direct waves from bombs at 30 fathoms to hydrophones at the same depth is practically equal to the average theoretical velocity from the surface to 30 fathoms.

A high velocity near the source of the explosion is indicated.

The velocity of sound in the mud floor of the Santa Barbara Islands Basin may have been about 1,580 meters per second.

The underwater explosions acted as a multiple source. The reason was not established by the experimental data.

Frequencies from 100 to 2,000 cps were observed with frequencies in the neighborhood of 100, 225, 475, and 900 cps predominating. These frequencies may have been inherent in the apparatus, but there is reason to believe that 200 cps was actually present in the bomb noises. The higher frequencies became relatively less prominent with increasing distance, the tendency being greater for the smaller bombs.

The direction of first motion associated with several ray paths showed a gradual change of sign. This was interpreted as evidence of frequency dispersion.

The trace amplitudes of the reflected impulses show a maximum at the distance the tangent ray recorded due to the focusing effect of the vertical velocity distribution.

The maximum distance over which diffraction effects were observed was much less for the direct waves than for reflections (*PR*1). This indicates that the energy resided largely in the higher frequencies at short distances and in lower frequencies at greater distances, agreeing with the observations on frequencies.

The long range transmission possibilities at velocity inversions was postulated.

THE EFFECT OF VARIATIONS IN CHEMICAL COMPOSITION ON THE VELOCITY OF SEISMIC WAVES IN CARBONATE ROCKS*

CARL KISSLINGER†

ABSTRACT

The variations of velocity in limestones have not fallen into as definite a pattern as have those in sandstones and shales. Although it is conceded generally that textural characteristics are more important than mineral content in determining the velocity in sandstones and shales, the possibility that the concentration of magnesium carbonate may appreciably alter the velocity in a limestone is investigated. It is found that dolomitization can be expected to have an effect on the velocity, but that effect is not certain, in that it depends on the nature of the dolomitization process. A volume for volume replacement of calcite by dolomite tends to increase the velocity, but dolomitization giving rise to local porosity, whether the resulting interstices are empty or filled by non-carbonate material, tends to decrease the velocity.

A knowledge of the velocity with which elastic waves are propagated through the materials that make up the solid body of the earth is either an essential tool or the final direct result of all phases of the analysis of seismic records. This is true in both exploration and earthquake seismology. Further, the possibility of using seismic velocity data as an aid to stratigraphic correlation has been increasingly recognized by geologists, who at the same time point out that the full realization of this possibility rests on the fuller understanding of the variable properties of rocks that influence the velocity.

It is, therefore, apparent that there are ample reasons for the numerous attempts that have been made to formulate the principles which govern the velocity of elastic waves in rocks. The general law yielding the velocity of seismic waves in a homogeneous and isotropic elastic solid in terms of the elastic constants and the density of the solid has long been known. The sedimentary rock column, to which we shall limit our attention, is neither homogeneous, as even the casual inspection of a typical well log will reveal, nor elastically isotropic, as measurements of velocity parallel and perpendicular to the bedding planes have shown (1).

Because the sedimentary strata depart so radically from this ideal behavior, the approach to the problem of determining the laws governing seismic wave velocities in them has been largely an empirical one.

Of the two types of elastic waves that can be propagated through the interior of an elastic solid, only the dilatational, or condensation-rarefaction, type was

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† Saint Louis University, Institute of Technology, St. Louis, Missouri.

considered in this investigation. This was necessitated primarily by the method of velocity determination, which did not permit the observation of the lower velocity shear wave. In all cases in the following discussion, the expressions "seismic wave velocity" or "wave velocity" will mean the dilatational wave velocity.

PRESENT KNOWLEDGE OF VELOCITY VARIATIONS IN LIMESTONES

The need for a review of previous research on the problem of velocity variations in sediments is largely obviated by an excellent paper by Krumbein (2), in which he brings to the attention of geologists the great potential value of seismic velocity data in stratigraphic correlation. In this paper, practically all significant work since the first discovery of the stratification of seismic velocities is summarized.

West (3) and Faust (4) have separately published empirical equations giving the velocity as a function of depth, in the first case, or depth and age, in the second. These equations are meant to apply only to sections of relatively pure clastic sediments, with limestones specifically omitted from consideration. In fact, the uncertainty of all generalized conclusions regarding limestones is a prominent feature of the literature on this subject.

An examination of published values for seismic velocities (5) in calcitic and dolomitic limestones reveals the following facts. The values range from 1.0 kilometer per second to 7.07 kilometers per second. For rocks located at the surface, the velocity tends to be higher in the older formations, but there are exceptions to this. The velocities for a given rock at depth are higher than for the same rock at the surface. Finally, the velocities in the dolomitic rocks are higher than in the calcitic ones.

In a significant paper that goes far in explaining these facts, Hughes and Jones (6) report the results of laboratory determinations of velocities in limestones, in which the rocks were subjected to pressures and temperatures of 0 to 1,100 kilograms per square centimeter and 25 to 175 degrees centigrade. Since the existence of a vertical thermal gradient within the earth's crust and the presence of overlying strata will increase both the temperature of and pressure on a rock as it is buried more deeply within the earth, these results should be valuable in accounting for the increase of the velocity at depth over the velocity in the same material when at the surface.

These experiments reveal that in all cases the velocity at depth is greater than the velocity at the surface for a given rock, but for different rocks, greater velocities can exist at lesser depths. In fact, in no case do the velocity versus depth curves for two carbonate rocks cross. Therefore, to some extent, at least, the velocity at depth depends on the velocity at the surface, so that if the velocity is greater in one limestone than another at the surface, it will also be greater at any given depth. These experiments do not explain, nor were they intended to explain, lateral variations in velocity.

To summarize briefly the facts about velocities in carbonate rocks, it may be said that, in general, the velocity increases with both age and depth of burial. Age alone is not a determinative parameter. For a given rock, the velocity increases with depth below the surface, but it is possible for a second rock, of the same age as the first and lying at a greater depth, to possess a lower velocity. The difference in velocity in rocks when located at depth seems to depend directly on the difference the velocities would show if the same rocks had been located at the surface. Finally the velocity in dolomitic rocks is in general higher than in calcitic limestones.

The work of Hughes and Jones offers evidence of an acceptable explanation for all of these facts except the lateral variation of velocity at a given depth.

In seeking the factors which control the surface values of the velocity, it is necessary to examine the physical properties of the material that determine the velocity—the density and the elasticity. These properties will depend on two things, first, the materials from which the rock is formed, and secondly, the manner in which these materials are assembled. The first is the mineral composition, and the second comprises all of the textural characteristics, such as grain size, cementation, and porosity. It is now generally conceded that the second feature is predominant in shales and sandstones. For limestones there is evidence that if one starts with a given specimen, the velocity can be controlled in a somewhat predictable manner by varying only the second factor. There is then left open to question, to what extent does the mineral composition control the values of the elastic constants and density initially. Can the lateral variations of velocity in limestones, or the exceptions to the general increase of velocity with age, be explained by differences in composition? And further, does the sedimentary process by which a given composition arises alter the effect of composition on velocity?

Field velocity measurements were made in an effort to find the answers to these questions. The rocks selected for the tests were to be as similar as possible in all respects except chemical composition.

The Test Formation and Test Strata

The problem of finding widely different compositions in rocks of approximately the same geologic age was solved by selecting the test strata from a formation that is marked by alternating beds of dolomitic and calcitic limestone. Of several available in the vicinity of St. Louis, Missouri, the St. Louis limestone, of Mississippian age, was chosen.

The problem of effects due to depth of burial was eliminated by making the measurements on surface exposures. However, such measurements always carry with them practically inestimable errors due to weathering effects. Since the actual velocity values are of only secondary interest here, and only the relative values are of interest, the fact that all rocks involved in the study are today found under identical environmental conditions made it possible to compare

them on the basis of the one distinct difference, their compositions. Rocks were chosen whose geologic histories were as similar as possible, except that somewhere in the past environmental conditions were such that some of these beds now contain relatively large amounts of magnesium carbonate, others little.

Horizontal exposures of the selected strata suitable for setting up the instruments were readily to be found in quarry floors. Of the many quarries in the St. Louis area, at only two had detailed tests of the rock composition been made, the St. Louis quarry of the Alpha Portland Cement Company, and the Fort Bellefontaine Quarry of the Missouri Portland Cement Company. Because of the careful control over the composition of this product required by modern engineering standards, both of these companies maintain fully equipped laboratories for the analysis of both the raw materials and the finished product.

Fortunately for this study, both companies had conducted extensive programs of test drilling on their respective quarry properties and chemical analyses of the drill cuttings, together with maps giving the location of the test holes, were generously made available to the author. Not only did these analyses reveal wide variations in composition in a relatively small vertical distance, but also the maps showed that these beds of widely varying composition form the floor in different parts of the two quarries.

The St. Louis formation is a member of the Meramec Group, of Middle Mississippian age (7). It forms the bedrock over a large part of the area that includes the City of St. Louis and St. Louis County, Missouri. The formation is composed almost wholly of dense limestones, with thin shale streaks occurring locally. In some parts the stone is almost lithographic, but varies to coarsely crystalline. The lower and upper parts are mostly thin-bedded with thicker beds in the middle portion.

Chert is found at all levels in the formation, though rather thick beds are found free of it. The formation is at least slightly magnesian throughout, although the magnesium carbonate content is low in many beds. Dolomitic limestone has been found in the formation in the following forms: interbedded with calcitic limestone, varying laterally from calcitic to dolomitic limestone, and in boulder-like masses embedded in the limestone.

The test strata at the Alpha Quarry are approximately forty feet above the contact of the St. Louis with the underlying Spergen limestone. The chemical analyses and direct examination show the quarry floor to exist of two main zones, one chiefly calcitic, the other dolomitic. The composition of the calcitic material varies from 92 to 97 percent calcium carbonate and 1.03 to 1.42 percent magnesium carbonate, while the dolomitic material contains 76 to 89 percent calcium carbonate and 5.5 to 13 percent magnesium carbonate.

The calcitic material is dense, finely crystalline limestone, medium gray in color. It occurs in a total thickness of about five feet. The dolomitic rock is light gray to buff in color, with thin laminae of dark gray or black material. It is very dense, almost lithographic, with a sugary appearance under high magnification.

The laminae are differentiable only on the basis of color, with no tendency for the rock to split along them. On the basis of the chemical analyses, this material is four to six feet in thickness.

The dolomitic layer lies under the calcitic one, and the quarry floor cuts across the bedding planes in such a way that the dolomitic rock is exposed at the western end of the quarry floor.

Because the Fort Bellefontaine Quarry is located about 23 miles northeast of the Alpha Quarry, and so is down the regional dip, the test strata here, while still part of the St. Louis, are considerably higher in the section. In fact, the contact with the overlying Ste Genevieve formation is thought to be near the top of the quarry face.

A wide variety of compositions and textures are to be found at this place, but only those rocks which formed part of the quarry floors could be used. There are two levels being worked in the quarry, so that the number of accessible layers was increased somewhat. Velocities were determined in three strata, two calcitic, one dolomitic. All three are dense, fine to medium crystalline. The calcitic material is dark gray, while the dolomitic rock is brown.

In summary, the strata in which the seismic velocity measurements were made are dense, crystalline to lithographic, calcitic and dolomitic limestones forming parts of the St. Louis formation of Mississippian age. The velocities were sampled in five distinct beds, three calcitic, the others dolomitic. Two of these are located near the bottom of the formation, the others near the top.

Experimental Procedure

The method used to measure the velocities in the selected strata is perhaps the most direct that can be devised for rocks *in situ*. It has been used by many investigators, although perhaps not on the scale of the present procedure, and a thorough discussion of the theory of the method or the instrumentation would be superfluous. Except for the distances from shot point to seismometers, the set-up was exactly that of refraction prospecting.

In order to eliminate the effects of structure on the wave paths, the converse of the goal of seismic prospecting, it was necessary to limit the seismometer spread length greatly. The twelve geophones were placed in a line 50 centimeters apart, and three records were made for each location, one with the shot 50 centimeters from each end of the spread, and one with the shot in the center of the spread.

One Number Eight electric blasting cap furnished ample energy at these short distances, and this was the source of seismic waves used. The cap was placed directly on the rock surface and covered with clay and then with a heavy stone.

The seismic equipment used was a commercial twelve channel portable refraction set manufactured by the Century Geophysical Company. The general characteristics of this type of equipment are so well-known that it is not neces-

sary to discuss them here. The one component of the apparatus of special importance here is the timing unit. A precision of one part in two thousand is claimed for the circuit. This is not as good as can be obtained by more elaborate devices, but the simplicity and freedom from maintenance problems are certainly compensating features in this portable equipment.

When the field procedure implied above had been carried out at each of the test locations, the next task was the reading of the travel-times. As would be expected, the observed step-out on the records was very slight, though quite definite. The records were read by means of a micrometer microscope with an accuracy well within the limits of error of the total procedure. This would have been an impossible task without the aid of some such precision instrument.

Analysis of the Field Data

With the travel-time data assembled for each record, the velocities were determined by the method of least squares. The three sets of data for each test location were computed separately, so as to have three independent determinations of the velocity. Further, this procedure eliminated errors in the velocities due to errors in reading the firing times, since the three straight lines obtained were not forced to have a common intercept.

It is most unlikely that the velocity value obtained from the least squares line is the true value, but rather a range of values may be obtained from the data within which the true value probably lies. If sufficient points were available, this range could be found by determining the standard error of estimate of the slope of the line. However, the standard error of estimate loses its significance for small samples, and special methods must be employed. By means of Student's "t" distribution, confidence limits of the velocity could be determined, limits with a well-defined significance, even for the smallest sample (8).

In this problem, 95 percent confidence limits were determined. These limits have the following meaning. From a single determination a statement is made that the true value of the velocity lies within this range. Because of the small sample on which it is based, the statement may be in error. However, if one hundred such determinations were made, 95 of the statements would be true on the average, assuming that the experimental procedure is properly designed so as to actually measure the velocity.

From these three determinations for each test location a final value of the velocity was decided upon. The required field data were then on hand to seek the answer to the original problem. These data are summarized in Table 1 for the Alpha Quarry, and Table 2 for the Fort Bellefontaine Quarry. The location numbers refer to the system of identification of the drill holes as set up by the quarries and are of no special significance here.

The velocity and chemical data were analyzed separately for each of the quarries. The velocities were plotted first against the relative calcium carbonate content, then the magnesium carbonate content, and finally against the content

TABLE 1

COMPOSITIONS AND VELOCITIES AT THE TEST LOCATIONS AT THE SAINT LOUIS QUARRY OF THE ALPHA PORTLAND CEMENT COMPANY

(All test holes were drilled and analyses made in the early part of 1948. Analyses supplied by Mr. John Benedek, chemist, Alpha Portland Cement Company.)

Location	$CaCO_3$	$MgCO_3$	Residual	Velocity
	(%)	(%)	(%)	(meters/sec)
13	97.2	1.03	1.77	2,143
14	89.5	5.51	4.99	1,837
17	94.82	1.16	4.02	1,641
18	94.82	1.42	3.76	1,717
21	96.20	1.10	2.70	1,600
32	96.75	1.06	2.19	1,450
34	92.31	1.12	6.57	1,809
42	76.44	13.06	10.50	1,396
43	83.48	8.46	8.06	1,402
44	87.64	5.62	6.74	1,278
46	84.11	9.21	6.68	1,576

TABLE 2

COMPOSITIONS AND VELOCITIES AT THE TEST LOCATIONS AT THE FORT BELLEFONTAINE QUARRY OF THE MISSOURI PORTLAND CEMENT COMPANY

(Three sets of test locations were drilled, each set being numbered from 1. The number prefixing the position number denotes the year of the test and analysis; 27 in 1927–1928, 30 in 1930–1931, 32 in 1931–1932. Only those locations are given at which the velocity was determined. Analyses supplied by Mr. Ralph Striker, chemist, Missouri Portland Cement Company.)

Location	$CaCO_3$	$MgCO_3$	Residual	Velocity
	(%)	(%)	(%)	(meters/sec)
27/1	56.85	37.46	5.69	1,825
27/3	94.80	trace	5.14	1,865
27/7	94.57	trace	5.43	1,737
27/8	93.43	1.26	5.31	1,958
30/4	72.87	21.71	5.42	1,929
32/3	97.66	.76	1.58	1,211
32/5	76.65	.96	2.39	1,726

of residual material, and regression coefficients of velocity and each of the rock constituents were computed.

The residual content was defined as 100 percent less the sum of the percentages of calcium and magnesium carbonate. Specific information as to the composition of the residual material was available at only a few locations, at which it was found to be largely silica, with varying amounts of the oxides of aluminum and iron, with small amounts of other metallic oxides.

The Fort Bellefontaine data indicate that velocity does not vary markedly with composition. A slight tendency for the velocity to increase as the relative amount of magnesium carbonate increases was found, but this tendency was most uncertain. The regression coefficients were: for calcium carbonate, -1.3 meters per second per percent; for magnesium carbonate, 1.1 meters per second per percent. Thus the increase with $MgCO_3$ is seen, but when 95 percent confidence

limits were computed for these coefficients, because of the scattered data it was found that either an increase or a decrease with either constituent might be reasonably expected from these data. Because of the slight range of values of the residual material content, no correlation with this variable was attempted.

On the other hand, the Alpha data, while more scattered, show a rather definite tendency for the velocity to decrease as the magnesium carbonate content increases, while the velocity changes less markedly as the calcium carbonate content is varied. The values found for the regression coefficients at Alpha are: for calcium carbonate, 4.6 meters per second per percent; magnesium carbonate, −29.3 meters per second per percent, and residual material −55.0 meters per second per percent. A consideration of the confidence limits indicated that these trends are much more definite than those at Fort Bellefontaine. The velocity is seen to depend much more on the content of magnesium carbonate and residual material than it does on the calcium carbonate content.

Thus, field conditions originally thought to be very similar yielded results that were distinctly different. It was then necessary to examine the total body of information on hand to determine if there was present any outstanding difference in the conditions at the two quarries that could reasonably explain the contradictory results.

Such an examination revealed one marked difference in the two sets of test rocks, and this is in the range of values of the residual material content at the two places. At Fort Bellefontaine, the residual material content is seen to be practically constant as the amounts of calcium and magesium carbonates vary, while at Alpha there is a considerable spread to these values, with the amount of residual material increasing in the more highly magnesian rocks.

Also it should be recalled at this point that in the description of the Alpha dolomite, thin laminae of dark material were mentioned. These could well be due to filling of interstices left as a result of the dolomitization process, and the increase in non-carbonate mineral content in the more magnesian rocks would indicate that this filling has been by arenaceous or argillaceous material.

Therefore, the field data indicate that if the magnesium carbonate content varies in such a way as to maintain the amount of non-carbonate material constant, the velocity is practically unchanged, but if the increase in magnesia is accompanied by the introduction of non-carbonate material into the rock, the velocity is decreased. These are the results of the field work.

In order to evaluate the significance of the assembled facts, it is necessary to examine the current thought on the process of dolomitization, in order to determine if the manner in which a given composition comes into being can be expected to have an influence on the elastic properties of the rock.

The Dolomitization Process

The origin of dolomite is still one of the unsettled questions of geology, and an extensive literature on this subject exists (9). It is known that carbonate rocks

exist in which the composition varies from almost pure calcite to practically pure dolomite, with all gradations in between (10). The texture of dolomitic limestones is commonly fine-grained and dense, with some coarsely crystalline occurrences having been described. Porosity varies from very compact to almost cavernous. Dolomitic beds are found in all parts of the stratigraphic column, but have their maximum development in the early Paleozoic and decrease roughly with time.

Dolomitic and magnesian limestones occur in a variety of forms which are summarized by Twenhofel as follows:

"1. Formation bodies.
2. Interbedded relationships.
3. Dolomitized coral reefs.
4. Dolomitized oolites.
5. Mottled limestones.
6. Nests or bunches of dolomite in limestone.
7. Dolomite passing laterally into limestone."

The dolomites under consideration in this study are interbedded between highly calcitic limestones. An example of a dolomite body of formational magnitude that is found in the St. Louis area is the Ordovician Joachim formation, which is found in thicknesses up to 125 feet (dilatational wave velocity, 6.4 kilometers per second). Other types of occurrences in the St. Louis formation have been mentioned above.

Of the several hypotheses suggested for the formation of dolomitic limestones, replacement of calcite by the mineral dolomite after the limestone has been deposited, but before it has been consolidated and has emerged from the sea, is supported by the strongest evidence. This type of marine alteration is believed to be the most likely source of dolomitic limestones of formational magnitude and those regularly interbedded between strata of calcitic limestone.

The environmental circumstances favorable for the formation of dolomite by marine alteration are thought to be quite different from those that do not favor. it. Warm, shallow sea water containing an abundance of carbon dioxide is considered to be most favorable. Time is also of importance if the process is to be carried through to completion.

The fact that porosity genetically related to dolomitization has been recognized for years is important to this study, because an inevitable increase in porosity with dolomitization, with the accompanying decrease in the elasticity, would mean a decrease in velocity with increasing magnesium carbonate content. This is in agreement with part of the field data of this investigation, but contradicts the data for dolomitic formations that have been published in the past.

The classical theory that a 12.3 decrease in volume will occur on the dolomitization of a calcitic limestone has been shown to be untenable in most cases. This hypothesis is intimately related to the nature of the replacement process itself. Landes (11) has pointed out the weaknesses of several earlier hypotheses set forth to explain dolomitization porosity, and proposes the following reasonable

explanation. Since the process of replacement is actually a combination of two processes, solution and precipitation (12), it is only in those cases in which solution goes on at so fast a rate that precipitation cannot keep pace, that a porous dolomite will be formed. Ordinarily the second process does keep pace, so that a volume for volume replacement results, yielding a compact rock.

The Effect of Dolomitization on Velocity

In order to gain some insight into the effect on the velocity that might be expected on theoretical grounds if calcite were to be replaced by dolomite, the pertinent constants of the two minerals were substituted into the equation for the dilatational wave velocity. Because of the anisotropicity of individual crystals, mean values of the elastic constants were employed. This anisotropicity is averaged out in a large aggregate of crystals oriented at random.

However, this procedure assumes that rocks are aggregates of crystals in perfect contact with each other, so as to form a continuum. This, of course, is generally not true. Therefore, it is expected that the elastic moduli of a rock would be somewhat less than those of crystals of the constituent minerals. This is actually borne out by the comparison of laboratory values for the elastic moduli of, say, calcite and limestone.

It was found as the result of this procedure, using values found in Birch, that under the very restrictive assumptions that a volume within a rock composed of calcite crystals in perfect contact with each other be replaced by an equal volume of the mineral dolomite, in such a way as to preserve the physical continuity of the rock, a velocity increase of about six percent would result. However, it is to be noted that the velocity found for calcite in this manner, 6.35 kilometers per second, is appreciably higher than any values for calcitic limestone at the earth's surface that have been reported, while that for dolomite, 6.75 kilometers per second, is only slightly higher than the field values.

Now, dolomite bodies are usually crystalline, and fine-grained at that, while calcitic limestones occur in which the calcite is in all manner of forms, from fine crystals to fragmental particles, bits of shells, oolites, and in which all manner of impurities may be found. Thus, if these velocities are looked upon as ideal upper limits for the surface velocity, it appears that dolomitic limestones quite reasonably approach the ideal more closely than do calcitic rocks. This fact makes plausible an even more pronounced effect of dolomitization on velocity than the six percent found above.

The severe restrictions placed on the nature of the replacement in the above discussion brings back into the picture the mode of origin of dolomitic limestones. A volume-for-volume replacement process, resulting in a compact dolomite, would come closest to satisfying these restrictions.

Consideration of all of the assembled facts leads to the following conclusions:

1. The observed increase in the velocity of dilatational waves in dolomitic limestones of formational magnitude over the values for calcitic limestones of

the same age may be explained on the basis of the relative values of the elastic constants and densities of the minerals calcite and dolomite. In those calcitic limestones that are not compact crystalline aggregates, the effect is even more pronounced.

2. Some part, at least, of the general increase of velocity with age may be explained by the parallel tendency for the extent of dolomitization to increase with age. This hypothesis furnishes a ready explanation for those exceptions to the increase, in that an older calcitic limestone in which the velocity is lower than in succeeding formations would be one whose depositional and post-depositional environments had not favored the concentration of magnesium carbonate.

3. The velocity in a dolomitic body that occurs interbedded between calcitic strata does not appear to be greatly affected if the replacement has been a volume-for-volume process. A slight tendency for an increase with dolomitization was noted, but it was quite uncertain.

4. In dolomitic limestones, in which an excess of porosity over the surrounding calcitic rocks is genetically related to the dolomitization process, the increase in magnesium carbonate content will be accompanied by a decrease in velocity.

5. In an impure dolomitic limestone, in which material other than dolomite and calcite occurs filling pore spaces which arose through dolomitization, the velocity decreases in the more magnesium rocks. These remarks are limited to rocks of uniform texture, and no conclusions are to be drawn for those rocks containing large nodules of non-carbonate material such as chert. The effect of the nature of the impurities and also the effects of large nodules should be material for further study.

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APPARENT RESISTIVITY CURVES FOR DIPPING BEDS*

M. UNZ†

ABSTRACT

The apparent resistivity calculations published for the two layer case with an inclined interface can be applied to small dip angles only. They are also limited to low ratios of the electrode spacing in relation to depth. This investigation covers the complete range of dip angles and electrode spacings.

The theory of reflected images is not generally applicable to the case of dipping layers, as assumed until now. Only for certain particular values of the dip do the methods of this theory remain in force. For all other dip angles practically sufficient results are obtainable by interpolation. The calculations are exact in cases with a bottom layer of very high or negligibly low resistivity. For the intermediate resistivity values an approximation method is available.

Simple algebraical expressions are obtained for the apparent resistivity curves. An approach to multilayer problems is discussed. The field procedure is outlined.

A. FORMULATION OF THE PROBLEM

In resistivity surveys over inclined underground layers with dip angles smaller than 10 degrees the inclination of the bottom bed is usually neglected in the calculations. It is then sufficient to find the depth of the interface at two or three points along the line of dip and to determine thus the inclination of the layer. For larger dip angles however, the altered boundary conditions can no longer be neglected in the interpretation.

Investigations have been published‡ for two layer cases with dip angles amounting to not more than 30 degrees. These investigations were also not extended over electrode spacings larger than three times the depth to the inclined interface, as they were based on the original image theory taken over from parallel layer problems. The present work attempts to establish the validity of this theory in application to dipping layers and to provide for a solution covering the entire range of dip angles and electrode spacings.

The results are calculated for Wenner set-ups laid out parallel to the strike (Fig. 1).

The dip angles are considered in relation to the ground surface, for simplicity the latter being shown horizontal.

Isotropic and homogeneous layers are assumed in all calculations.

B. THE FIELD OF A SINGLE SOURCE

1. Applying the method of images

When a point source is placed at the ground surface over a number of parallel underground layers, the current distribution is represented by the resulting

* Manuscript received by the Editor November 30, 1951.

† Mekoroth Water Co., Tel-Aviv, Israel.

‡ R. F. Aldredge, The Effect of Dipping Strata on Earth Resistivity Determination; Colorado School of Mines Quart., 32 (1), (Jan., 1937), 169–186.

B. S. Sanjeevareddi, Thesis 1936, No. T 567; obtained by courtesy of the Colorado School of Mines.

field of a double series of images located on the perpendicular through the point source.*

In the two layer case the position of the images can be physically demonstrated by replacing the interface between the two layers by a mirror and providing a second mirror parallel to it and at equal distance over the ground surface. When looking at one of those two mirrors from any point on the ground surface, an endless series of images of the original current source will appear

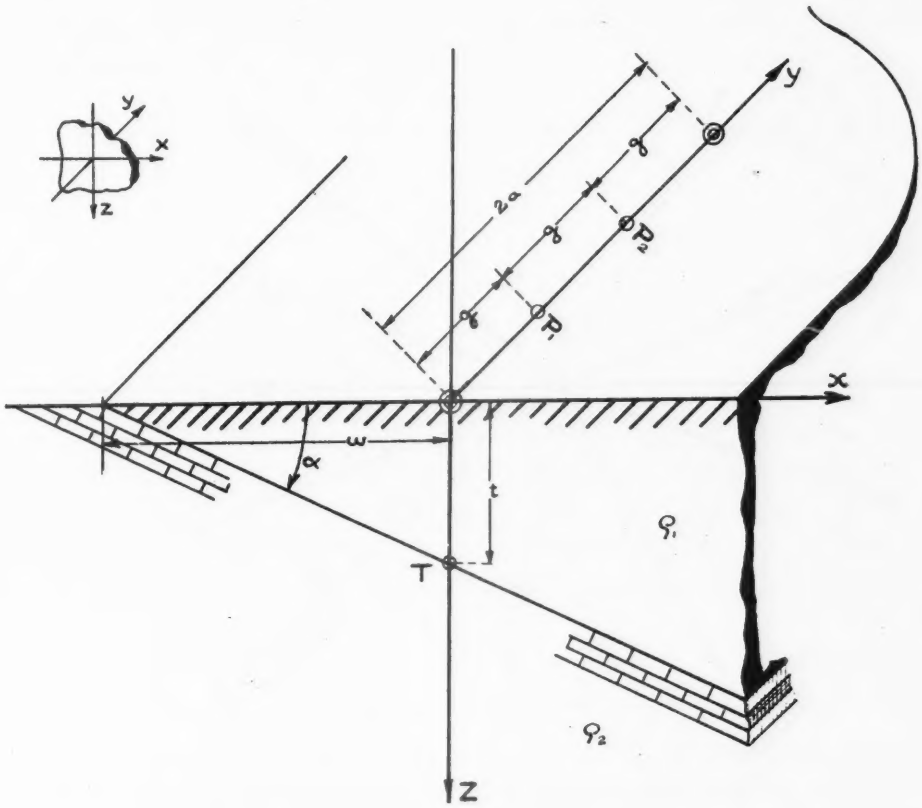

FIG. 1. Wenner set-up in direction of the strike.

by multiple reflection in the mirrors. The beams of light reflected from the bottom mirror superimposed over the direct beams originating from the real source, will then produce a pattern which is identical with the electrical current distribution in the top layer. As long as the bottom layer consists of an ideal insulator, the two mirrors are supposed to reflect perfectly. Beds of finite resistivity are represented by mirrors which are absorbing part of the light energy.

* F. Ollendorff, Erdströme, Berlin, (1928), 69.

In the case of non parallel layers a general analytical proof is not available for the method of reflected images. We shall therefore, investigate by an example at hand to what extent the method is physically justified.

The field of a point source at the ground surface over an underground dipping layer of infinite depth has to be reconstructed. For this purpose we replace the interface by a plane mirror and provide a second mirror symmetrically over the ground surface. A number of images of the current source will now appear in

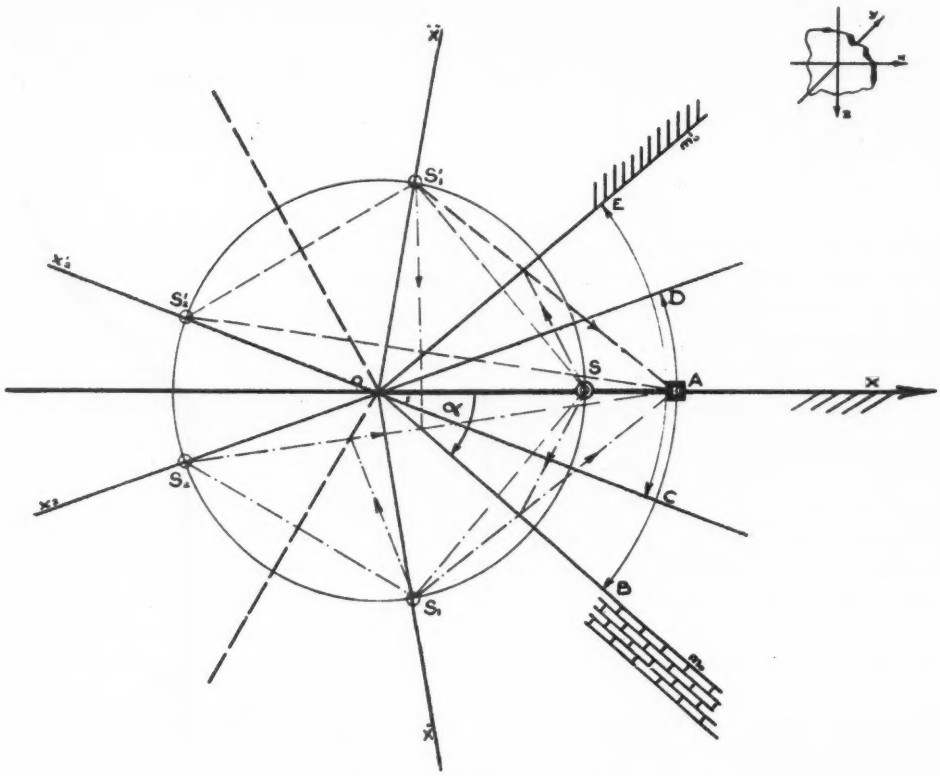

FIG. 2. Images of a point in two intersecting mirrors ($\alpha=40°$).

the mirrors. It will be proved in the following that not all the beams originating from these images are complying with the basic conditions of the electrical field.

Let us assume a current source in point S on the ground surface, located over an insulating dipping layer making an angle of $\alpha=+40°$. We replace the interface by mirror m_0 and provide a second mirror m_0' at an angle $\alpha'=-40°$ over it, as shown in the normal cross-section, Figure 2.

When viewed from point A in the x-y plane the source S appears in mirror m_0 as the image S_1 and in mirror m_0' as S_1'. The second image S_2, seen in mirror m_0, can be traced as a reflection of S_1 or S_1', as indicated by the dotted lines. The same applies to image S_2' in mirror m_0'.

The two primary images S_1 and S_1' are visible from any point located in the space between the two mirrors; whereas the secondary image S_2 is visible in mirror m_0 only from points within the sector *BOD* of the cross-section. It disappears as soon as the observer's eye crosses the line *OD*, owing to the edge of mirror m_0' interfering with the reflected beams of light at point *O*. Similarly image S_2' remains visible in mirror m_0' only to observers looking from the sector *EOC*.

The fact that the reflected beams originating from S_2 and S_2' are partly blocked by the edges of the mirrors, is not consistent with the basic conditions

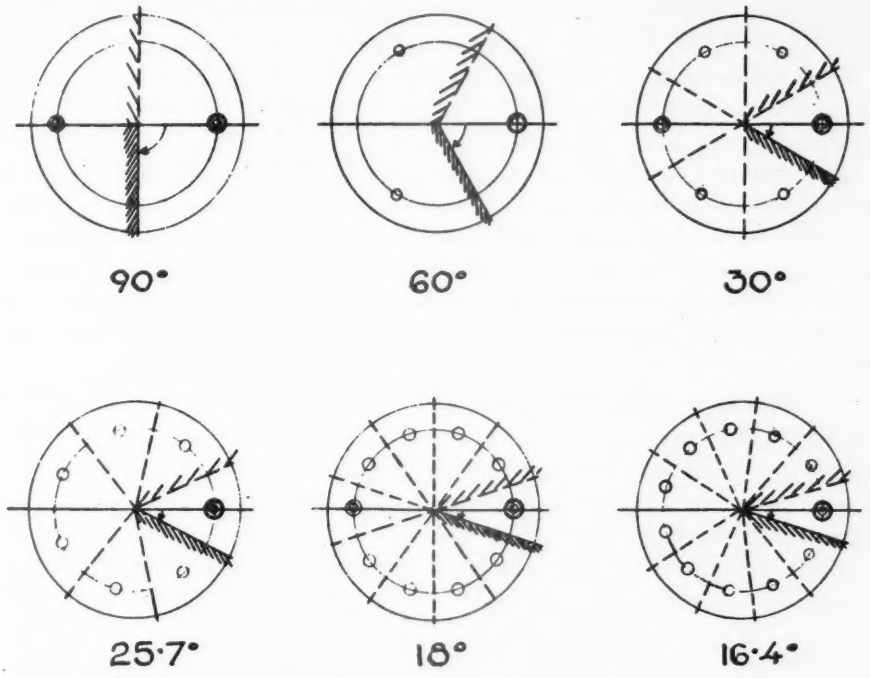

FIG. 3. Examples for the distribution of reflected images at various dip angles α.

of the electrical field. We see that the beams of light in the optical example are limited by the physical dimensions of the mirrors, whereas an infinite space had been assumed for the vectors of the equivalent electrical field. The resulting current distribution, and in particular the field at the boundaries, may therefore be different from the picture obtained by means of the reflected images.

With increase of the dip angle α the images S_2 and S_2' move towards the axis of abcissae x-x. When looking from the x-y plane both images reach the x-axis and overlap when α becomes 45°. By increasing α still further we find that the images S_2 and S_2' suddenly disappear, producing thus a discontinuity point in the representation.

Amongst the distributions of images corresponding with the various dip angles α, there are those in which the source S and its reflections produce a geometrically symmetrical pattern, in relation to the intersection point O (Fig. 3). For sym-

metry reasons only with these particular angles are the boundary conditions fulfilled and the equipotential planes of the electrical field identical with those in the optical example.

In all other cases a congestion or a thinning out of the reflected images takes place in the vicinity of the negative x-axis, thereby producing a cyclic disturbance of the field symmetry. Consequently the general application of the method of reflected images to dipping beds must lead to a distortion of the equipotential planes, with resulting discontinuities and errors in the calculated results.

2. Values of the Dip Angle

a) *Dipping Layer of High Relative Resistivity.*

For a non-conducting bottom layer the source and all its reflected images are of equal sign.

The examples in Figure 3 cover this case. In addition to the perfectly symmetrical set-ups for $\alpha = 60$, 25.7 and 16.4 degrees, those for 90, 30 and 18 degrees could also be considered, provided that only half the intensity of the two overlapping images on the x-axis would be taken into account. This appears permissible, as these are the discontinuity points in which the two overlapping images are seen as single reflections only, whereupon with increasing α, they vanish entirely.

The dip angles α determining a symmetrical distribution of images are therefore given by

$$\alpha = \frac{180^\circ}{q}, \tag{1}$$

wherein q denotes an integer.

The number of images n_0 reflected in one mirror is then obtained from

$$n_0 = \frac{1}{2}\left(\frac{360^\circ}{2\alpha} - 1\right) = \frac{90^\circ}{\alpha} - 0.5. \tag{2}$$

TABLE 1

DIP ANGLES AMENABLE TO CALCULATION IN THE CASE OF A NONCONDUCTING BOTTOM LAYER

Dip angles α in degrees	90	60	45	36	30	25.7	22.5	20	18 · · ·	8.6 · · ·	6 · · ·
Number of images: n_0	0.5	1	1.5	2	2.5	3	3.5	4	4.5 · · ·	10 · · ·	14.5 · · ·

Table 1 gives the number of images calculated from above expression. With a further decrease of the dip angle we approach the case of parallel layers with an infinite number of reflections.

b) *Dipping Layer of High Relative Conductivity.*

In the case of relatively high conductivity of the bottom layer the images must be provided with alternate signs.

The number of set-ups listed in Table 1 will then have to be reduced as only those distributions of sources and sinks will remain symmetrical in which the last image, whatever its sign, falls on the x-x-axis.

The corresponding dip angles are then given by

$$\alpha = \frac{90^\circ}{q}, \tag{3}$$

wherein q again denotes an integer.

Only half of the dip angles shown in Table 1 are now amenable to calculation. The resistivity curves $s=f(\alpha)$, owing to their slight curvature, can still be plotted with all the accuracy required.

c) *Intermediate Cases.*

The extension of the theory of images to bottom layers with intermediate resistivity values is subject to certain limitations.

For two layers of the resistivities ρ_1 and ρ_2 the reflection factor is expressed by

$$k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}. \tag{4}$$

The intensities of the consecutive images must now be reduced by multiplying them by the respective powers of the reflection factor k, k^2, k^3 . . . , as is done for parallel layers.

The resulting configuration of sources and sinks will no longer be symmetrical and will lead to a distortion of the equipotential plane assumed for the interface. The deviations caused by this distortion are negligible at small absolute values of the reflection factor k and also at sharp dip angles, due to the large number of images then involved.

The error in the calculations is largest for points located on the intersection line of the interface with the ground surface (Point O in Figure 2), and decreases rapidly when moving away from this line. Provided the exact value of the apparent resistivity on the intersection line can be found, most of the error may be eliminated.

3. *The Potential Function*

The value of the potential at the ground surface must be found which is produced by a current (I), sent into the ground from a point source S. The resistivity of the top layer is ρ_1, that of the bottom layer ρ_2. Let the bottom layer be dipping under an angle α, in our instance 9 degrees (Fig. 4).

The reflection method is applicable here without regard to the sign of the reflection factor k. The two layer case can thus be replaced by an infinite homogeneous medium of resistivity ρ_1 with a number of reflected sources located in it. The current leaving the source S is then $2I$; that leaving the n-th reflection S_n has the intensity of $k^n \cdot 2I$. The potential produced by this imaginary system of sources is found by superimposing the potentials of the original source and each

of its reflections. By physical experience it is confirmed that the resulting potential is also a continuous function.

A rectangular coordinate system is laid through the source S, with the x- and y-axes on the ground surface, whereas the z-axis is vertical. The y-axis is

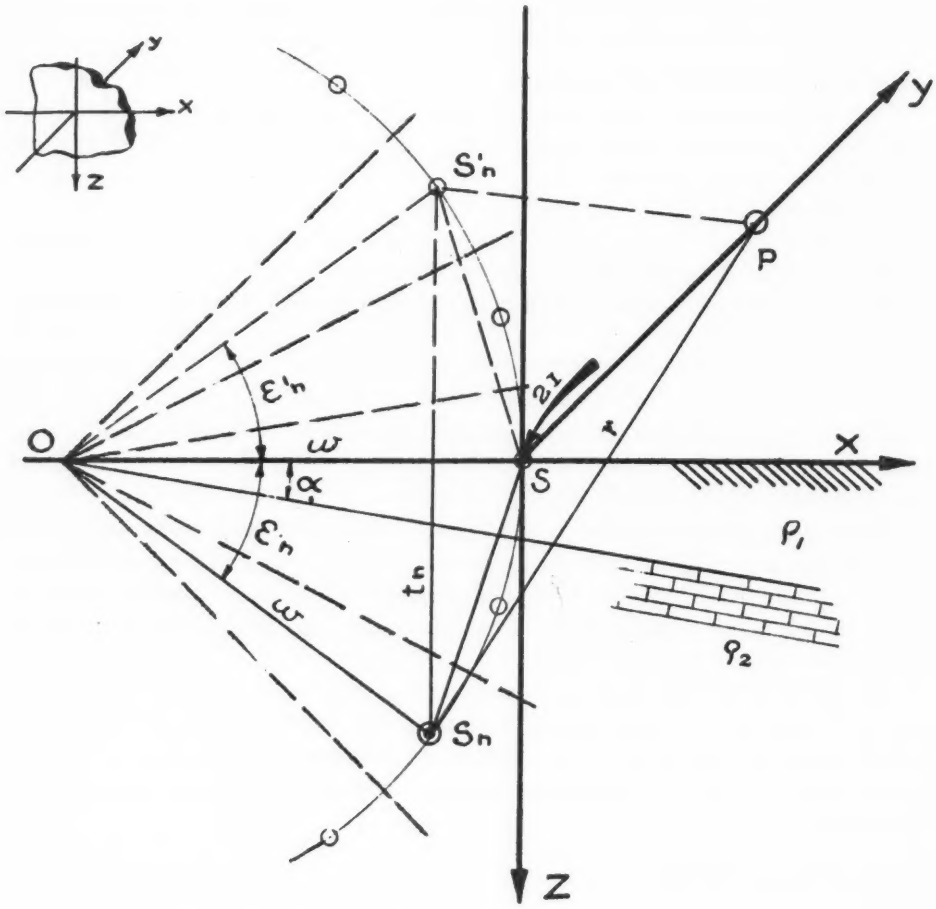

FIG. 4. Coordinates for the potential function ($\alpha=9°$; $n_0=9.5$).

assumed parallel to the strike of the dipping layer; the positive end of the z-axis is directed downwards.

The potential produced by the n-th image S_n of the source S in a point P on the y-axis is then

$$\phi_n = \frac{k^n \cdot I}{2\pi} \cdot \rho_1 \cdot \frac{1}{r} \cdot \tag{5}$$

With w representing the distance of S_n from the intersection point, and the corresponding angle given by

$$\epsilon_n = 2n\alpha, \tag{6}$$

the distance of P from S_n can be expressed by

$$r = [(w - w\cos\epsilon_n)^2 + (w\sin\epsilon_n)^2 + y^2]^{1/2}, \tag{7}$$

which leads after some transformation to the value of the potential

$$\phi_n = \frac{k^n \cdot I}{2\pi} \cdot \rho_1 \cdot \frac{1}{[4w^2\sin^2(n\alpha) + y^2]^{1/2}}. \tag{8}$$

This function is symmetrical in relation to the x-axis and becomes zero for infinite values of the ordinates y. With increasing w the potential decreases, also converging to zero. At very small angles ϵ_n the product $2w\cdot\sin(n\alpha)$ approaches the value $w\epsilon_n$, which is then equivalent to the depth t_n of the n-th image under the surface; equation (8) thus reduces to the known expression for parallel layers.

The resulting total potential ϕ_t is obtained as the sum of the potential ϕ_0 of the original source S and of the potentials ϕ_n and ϕ_n' derived from each of the images. In points of the x-y plane, where the corresponding components ϕ_n and ϕ_n' are equal, there follows for the total potential

$$\phi_t = \phi_0 + 2\sum_{n=1}^{n_0} \phi_n \tag{9}$$

over all images appearing below the x-axis. For images overlapping on the x-axis, as mentioned in the previous chapter, only half of the respective ϕ_n shall be taken.

C. APPLICATION TO WENNER SET-UP

1. *Directing the Set-Up Axis*

The values of the potential expressed in equations (8) and (9) can be applied to any electrode set-up required. We shall do it for the Wenner set-up laid out in the direction of the strike, as indicated in Figure 1.

This set-up is the most convenient for field requirements. It leads to continuous resistivity curves as long as it remains on top of the dipping layer, corresponding with positive values of the distance w. We may vary the electrode spread g or move the set-up parallel to the strike and at right angles to it, without changing the basic boundary conditions.

The expression for the apparent resistivity ρ_a will be derived in the following on similar lines as that for parallel layers.

The voltage U_p between the Probes P_1 and P_2 is given by the difference of the potentials produced by each of the power electrodes in these two points. For symmetry reasons and with reference to (9) we obtain

$$U_p = 2\left[(\phi_{1,0} - \phi_{2,0}) + 2\sum_{n=1}^{n_0}(\phi_{1,n} - \phi_{2,n})\right]. \tag{10}$$

By substituting in this expression ϕ_0 and ϕ_n by values from equation (8), and setting herein for y_1 and y_2 the distances g and $2g$ respectively, we arrive at

$$U_p = \frac{1}{\pi}\cdot\rho_1\cdot\left\{\frac{1}{2g} + 2\sum_{n=1}^{n_0}\left[\frac{k^n}{(4w^2\cdot\sin^2 n\alpha + g^2)^{1/2}} - \frac{k^n}{(4w^2\cdot\sin^2 n\alpha + 4g^2)^{1/2}}\right]\right\}. \tag{11}$$

In order to reduce this expression to the coordinates used for standard resistivity diagrams, we replace the distance w by the depth t

$$w = t\cdot\cot\alpha; \tag{12}$$

introduce the ratio

$$p = \frac{g}{t} \tag{13}$$

for the abscissae of the diagrams and the "Relative Apparent Resistivity"

$$s = \frac{\rho_a}{\rho_1} \tag{14}$$

for the ordinates; the apparent resistivity ρ_a being defined by the equation

$$U_p = \frac{I}{2\pi g}\cdot\rho_a. \tag{15}$$

As a result we obtain

$$s = \frac{\rho_a}{\rho_1} = 1 + 4\sum_{n=1}^{n_0}\left\{\frac{k^n}{\left[1 + \left(\frac{2\cot\alpha\cdot\sin n\alpha}{p}\right)^2\right]^{1/2}} - \frac{k^n}{\left[4 + \left(\frac{2\cot\alpha\cdot\sin n\alpha}{p}\right)^2\right]^{1/2}}\right\}. \tag{16}$$

For very small dip angles α this equation reduces to the well known expression for parallel layers with an infinite number of images

$$s = 1 + 4\sum_{n=1}^{\infty}\left\{\frac{k^n}{\left[1 + \left(\frac{2n}{p}\right)^2\right]^{1/2}} - \frac{k^n}{\left[4 + \left(\frac{2n}{p}\right)^2\right]^{1/2}}\right\}. \tag{17}$$

For $\alpha = 90°$ there remains one double image on the x-axis and we obtain, upon substituting the value of w from (12),

$$s = 1 + 2k\left\{\frac{1}{\left[1+\left(\frac{2w}{g}\right)^2\right]^{1/2}} - \frac{1}{\left[4+\left(\frac{2w}{g}\right)^2\right]^{1/2}}\right\}, \qquad (18)$$

which is in agreement with Tagg's formula for the vertical fault.*

2. Apparent Resistivity Curves

a) *General.*

The apparent resistivity diagrams are similar to those for parallel layers (Figs. 6 and 7). All curves start from the relative apparent resistivity $s=1$ at $p=0$ and asymptotically approach a constant value s_∞ with increasing p.

At very small p, corresponding to a large depth t in relation to the probe spacing g, the apparent resistivity ρ_a must be equal to the resistivity of the top layer ρ_1.

At very large values of p the depth t may be neglected in relation to the probe spacing g, so that the probes then appear located on the intersection line of the interface with the ground surface. In view of the large electrode spreads then required, the current paths between the probes may be assumed to be parallel at the ground surface. The value of the apparent resistivity follows then from the following simple consideration.

In a very thin tube of the radius r, laid coaxially with the set-up (Fig. 5),

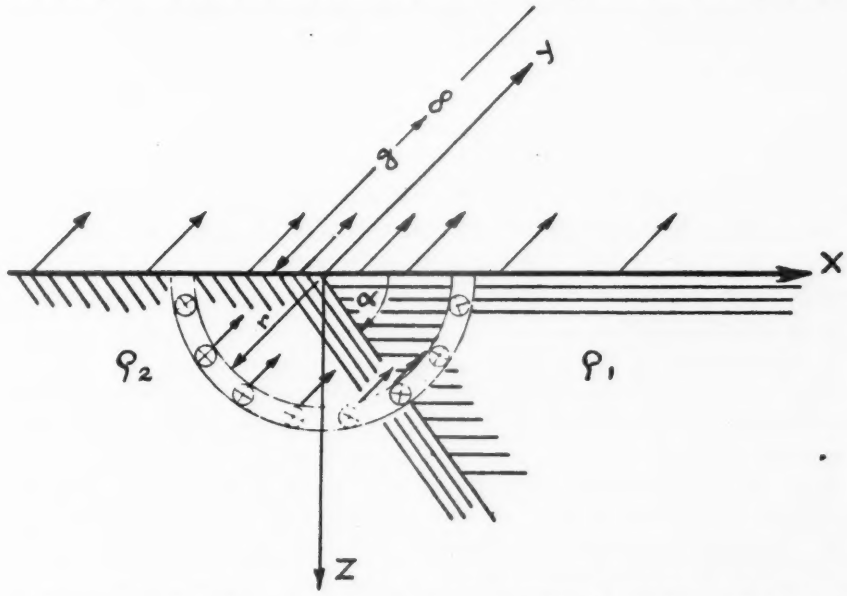

FIG. 5. Cross section through a current tube at the ground surface for very large values of $p=g/t$.

* C. A. Heiland, *Geophysical Exploration*, New York (1940), 721.

the current densities i are inversely proportional to the resistivities ρ_1 and ρ_2. The resulting mean current density over the normal cross-section of this tube i_a is then given by

$$i_a = \frac{C}{180}\left[\alpha \frac{1}{\rho_1} + (180 - \alpha)\frac{1}{\rho_2}\right], \tag{19}$$

wherein C is a constant.

As the same relation applies to all tubes in the zone considered and the resulting apparent resistivity ρ_a is inversely proportional to the mean current density, we can set

$$\rho_a = \frac{C}{i_a} = \frac{180}{\frac{\alpha}{\rho_1} + \frac{180 - \alpha}{\rho_2}}. \tag{20}$$

Upon dividing this expression by ρ_1 we arrive at

$$s_\infty = \frac{\rho_a}{\rho_1} = \frac{1}{\frac{\alpha}{180} + \left(1 - \frac{\alpha}{180}\right)\frac{\rho_1}{\rho_2}} \tag{21}$$

as the relative apparent resistivity for very large values of the abscissae p. At $\alpha = 90°$ this expression reduces to

$$s_\infty = 2\frac{\rho_2}{\rho_1 + \rho_2}; \tag{22}$$

and at $\alpha = 0°$ to

$$s_\infty = \frac{\rho_2}{\rho_1}, \tag{23}$$

which are the two extreme asymptote values for the apparent resistivity curves.

Diagrams can be plotted for constant values of the reflection factor k or for constant dip angles α. The computation of these curves is much easier than for parallel layers, especially at large dip angles when only a few reflected sources have to be calculated.

b) *For Reflection Factor* $k = \pm 1$.

The curves in Figures 6 and 7 have been drawn out for various parameters α. The diagrams are exact and their asymptote values check with those obtained from equation (21).

For very high relative resistivity of the bottom layer, $k = +1$ (Fig. 6), the asymptote value at $\alpha = 0°$ is $s_\infty = \infty$. At a dip angle $\alpha = 90°$ it amounts to $s_\infty = +2$, with s remaining constant for all values of the abscissae p. This is the case of the "Vertical Fault," with the set-up located over the fault plane and the apparent resistivity remaining independent of the electrode spread.

The fact that the $s=f(p)$ curves are intersecting at their beginning requires particular attention at the interpretation of survey results. This intersection can be qualitatively explained by the varying share of the ρ_1 and ρ_2 areas in carrying the bulk of the current. If we consider the interface of an insulating layer ρ_2 turning around point T at a constant depth t (Fig. 1), we will find that at large values of t the effective resistance of the ρ_1 medium grows with increasing dip

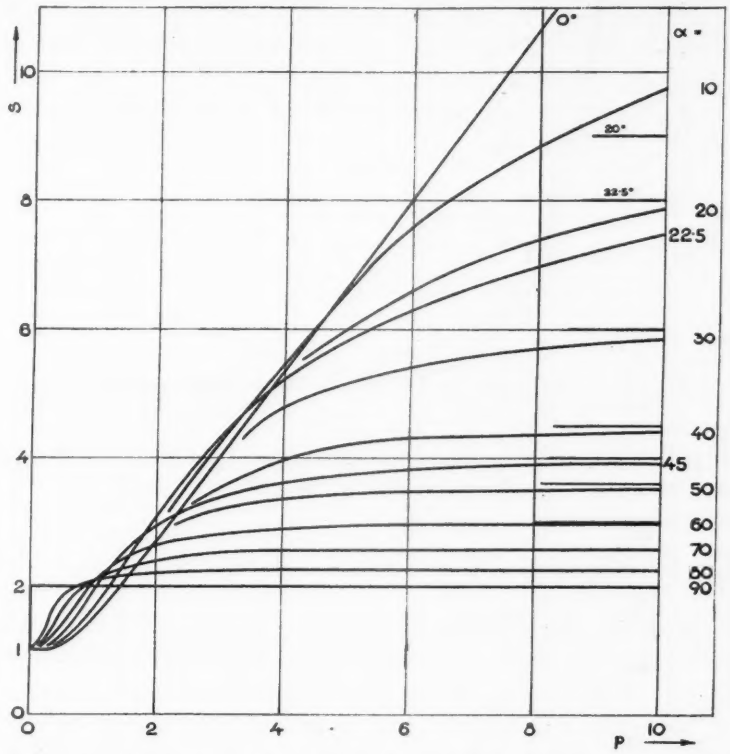

FIG. 6. Apparent resistivity curves for a dipping layer of high relative resistivity ($k=+1$) at constant dip angles α.

angle, due to the reduction of cross-section in the zone of high current densities. At smaller depths t the increase of the cross-section of the ρ_1 medium below point T outweighs the effect of the reduction on top. As a result the trend of the apparent resistivities with varying p changes, producing thus an intersection of the $\alpha=$ const., curves at the intermediate values of p.

In the diagram for $k=-1$ (Fig. 7), *viz.* very low relative resistivity of the dipping layer, the above features are less pronounced. This is mainly due to the fact that the apparent resistivity becomes zero for survey points nearing the intersection line with the ground surface. As a result all $\alpha=$ const., curves asymptotically approach the same $s=0$ line for large values of p. The curves start from $s=1$ as usual, and intersect in a similar way as shown for $k=+1$.

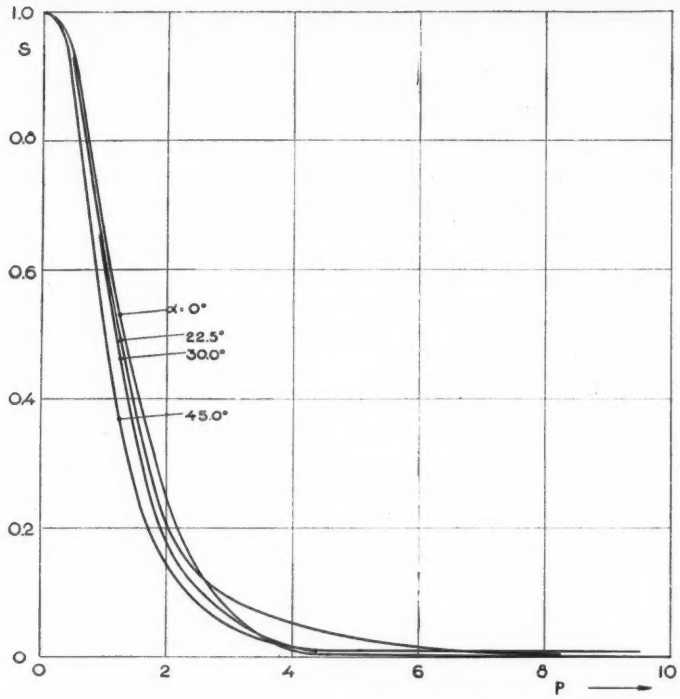

FIG. 7. Apparent resistivity curves for a dipping layer of high relative conductivity ($k=-1$) at constant dip angles α.

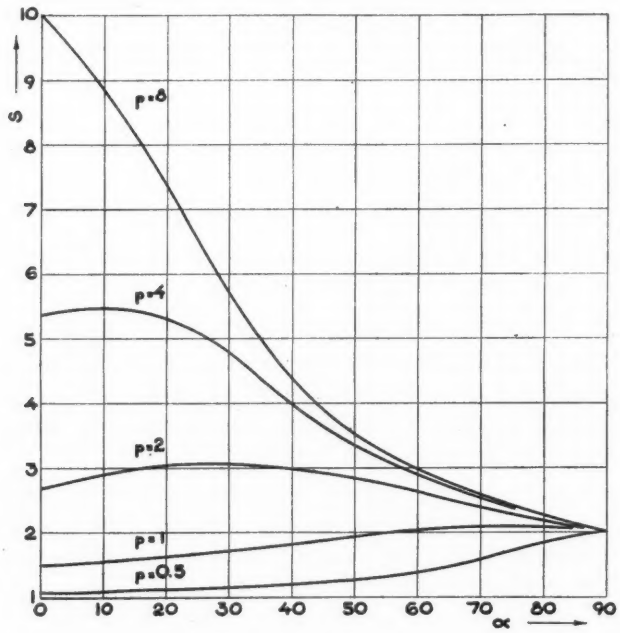

FIG. 8. Apparent resistivity as a function of the dip angle α for a bottom layer of high relative resistivity ($k=+1$).

In case resistivity curves are required for angles in addition to those listed in Table 1, the values can be taken from $s=f(\alpha)$ diagrams at constant values of p, as shown in an example for $k=+1$ (Fig. 8). All curves meet there at $s=2$ and $\alpha=90°$; the intersection points of Figure 6 appearing this time as points of equal ordinates for a given value of p.

c) *For Reflection Factors* $0<|k|<1$.

For dipping layers of a resistivity ρ_2 of the same order of magnitude as that of the top layer, the maximum error resulting from the image theory occurs in the asymptote values of $s=f(p)$ curves, as explained above. The ratios of the calculated asymptote values s_∞' to the true values s_∞ are given in Table 2.

TABLE 2

CALCULATED ASYMPTOTE VALUES OF THE RELATIVE APPARENT RESISTIVITY s_∞' IN RELATION TO TRUE VALUES s_∞.

k	+0.2	+0.4	+0.6	+0.8	+1.0	−0.2	−0.4	−0.6	−0.8	−1.0
α Degrees	s_∞'/s_∞					s_∞'/s_∞				
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
15	1.04	1.12	1.19	1.24	1.00	0.97	0.94	0.89	0.67	1.00
30	1.07	1.14	1.17	1.14	1.00	0.95	0.96	1.05	1.29	1.00
45	1.08	1.12	1.11	1.08	1.00	0.85	0.72	0.57	0.28	1.00
60	1.09	1.11	1.10	1.06	1.00	—	—	—	—	—
90	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

For parallel layers $\alpha=0°$ and for the vertical fault $\alpha=90°$ the error is nil at all values of the reflection factor.

At the intermediate dip angles and for positive k the calculated value is always larger; its peak moving with the dip angle and reaching a maximum of $1.24s_\infty$ at $\alpha=15°$, $k=+0.8$. The calculated and the true asymptote values plotted over the dip angle α are shown in Figure 9.

For negative reflection factors an oscillation of the error takes place, due to the varying distribution of the reflected sources and sinks. For $k=-0.2$ and -0.4 the calculated s_∞' are smaller than the true asymptote value, the absolute error remaining within the limits obtained for positive k. At lower reflection factors the error starts changing sign, the calculated values coming then down to $s_\infty'=0.28s_\infty$ for $\alpha=45°$, $k=-0.8$. It should however be noted that this error is related to a point on the intersection line of the dipping interface with the ground surface. Furthermore the true asymptote value itself amounts there to less than $s_\infty=0.15$.

Considering the fact that every calculated curve is exact at small p, and its true asymptote value for large p is also known, it will be found convenient to correct the curve by modifying its asymptote only. A corrected reflection factor k' must be substituted in the equation to adapt its asymptote to the true value s_∞.

The corrected curve will osculate with the exact diagram at both ends, at small and at large values of p. The remaining largest error will thus move to a

point about the middle of the curve, now being reduced to a fraction of the asymptote errors listed above.

For a comparison we shall first apply the above approximation to parallel layers, for which the exact $s=f(p)$ curves are well known. In the example chosen not more than $2\frac{1}{2}$ reflections will be considered per half-space, instead of the infinite number of images required for an exact solution. The reflection factors

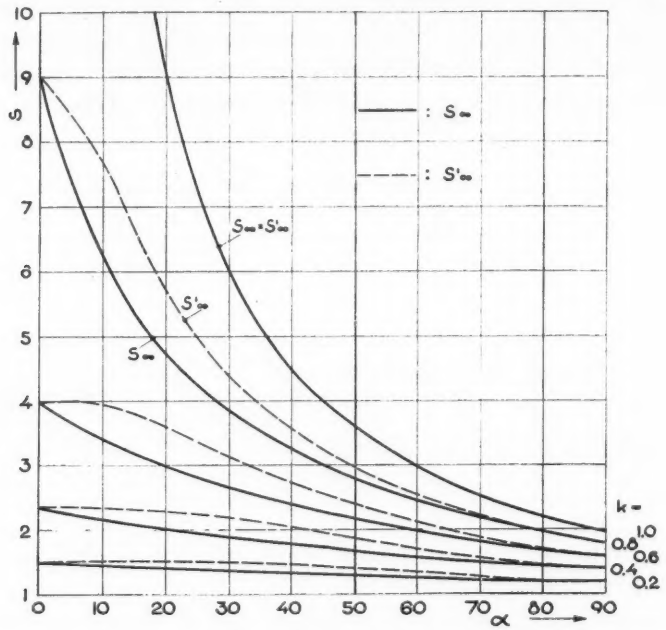

FIG. 9. Asymptote values of the apparent resistivity curves as a function of the dip angle α for constant reflection factors, $k>0$.
——— = Exact values, s_∞.
– — – = Values s_∞', as obtained from Image Theory.

shall be $k=+0.5$ and $k=-0.5$. The corresponding ratios s_∞'/s_∞, as obtained by means of equation (17), are then equal to 0.875 and 1.125 respectively.

When introducing the true asymptote values s_∞, into the expression for

TABLE 3

APPROXIMATION METHOD APPLIED TO PARALLEL LAYERS

Calculated values of the relative apparent resistivity s' in relation to the exact values s, when reducing the number of images to $n_0=2.5$.

p	0	1	2	4	6	8	10	∞
k	s'/s							
+0.5	1.00	1.03	1.06	1.08	1.08	1.08	1.05	1.00
−0.5	1.00	0.98	0.93	0.94	0.98	0.99	1.00	1.00

s_∞' deduced from (17), we arrive at the equivalent reflection factors k' for which the approximation curves shall be plotted. The deviation of these approximate characteristics from the exact diagrams is expressed by the ratios s'/s given in Table 3. Herein we see that the maximum errors have been shifted to a limited zone at lower values of p, as expected, and are reduced to 8 and 7 percent respectively.

For the plotting of dipping layer curves the equivalent reflection factors k'

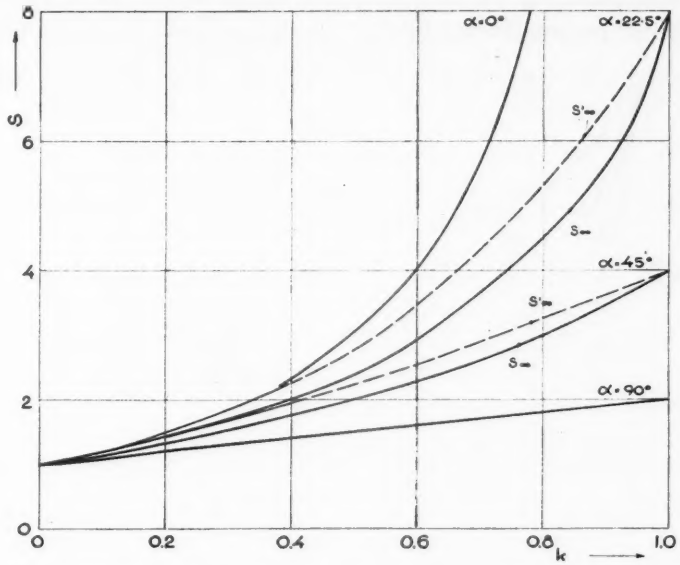

FIG. 10. Auxiliary diagram for the determination of the equivalent reflection factor k' at $0<k<+1$.

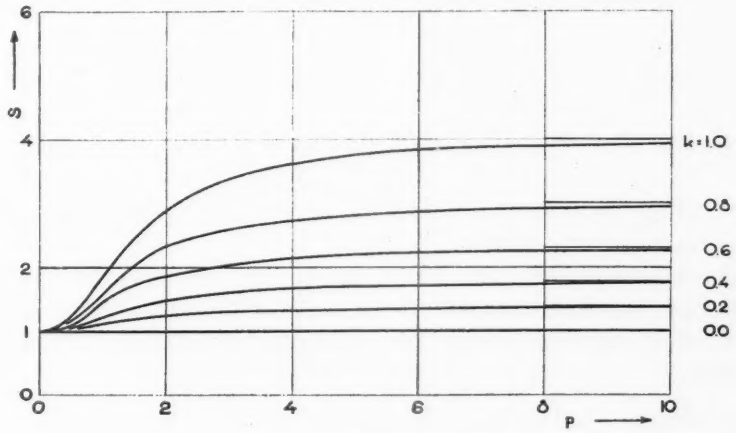

FIG. 11. Apparent resistivity curves for a dip angle $\alpha=45°$ at constant values of the reflection factor $0<k<+1$.

are best obtained graphically from an auxiliary diagram $s_\infty = f(k)$ for $\alpha = \text{const.}$ (Fig. 10). The values of k' are there scaled off the points of equal ordinate on the s_∞- and s_∞'-curves. Thus for example has been obtained $k' = 0.52$ for $k = 0.6$ at $\alpha = 45°$.

Two sets of resistivity curves, for $\alpha = 45°$ and $\alpha = 22.5°$ have been approximated in this way (Figs. 11 to 14). All graphs start from $s = 1$, as in the case of horizontal layers, but their s_∞ values are different, depending on the dip angle α. When superimposing the corresponding diagrams it will be found that the curves for equal parameters k intersect in a similar way as shown in Figures 6 and

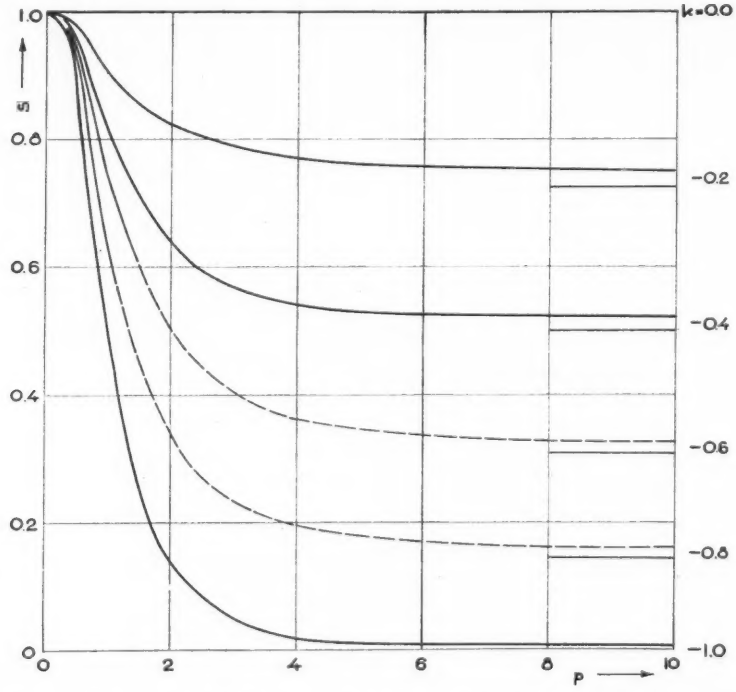

FIG. 12. Apparent resistivity curves for a dip angle $\alpha = 45°$ at constant values of the reflection factor $0 > k > -1$.

7 above. At negative reflection factors the variation of α again very little affects the apparent resistivity values.

Depth determinations are carried out in the usual way by matching the shape of the curves. It is then convenient if one of the parameters, the reflection factor or the dip angle, is known from other investigations to facilitate the interpretation.

3. *Approximation of Multilayer Problems*

The above calculations can be extended to the investigation of more than two layers in a similar way as done for parallel underground beds.

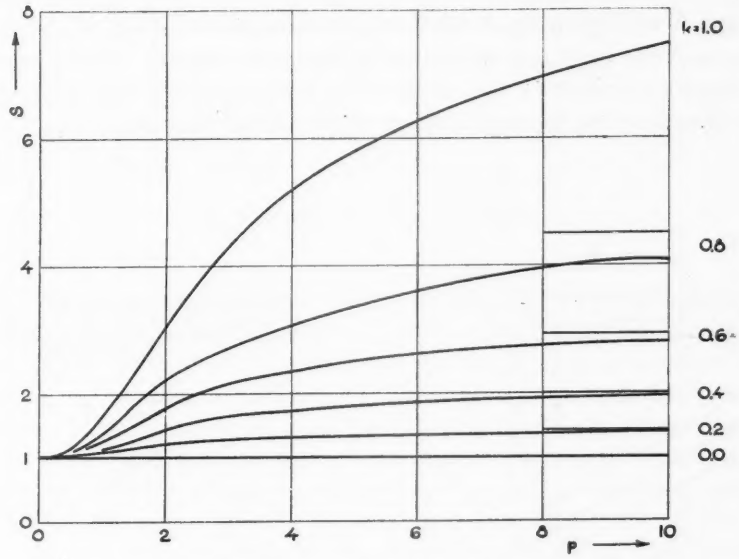

FIG. 13. Apparent resistivity curves for a dip angle $\alpha=22.5°$ at constant values of the reflection factor $0<k<+1$.

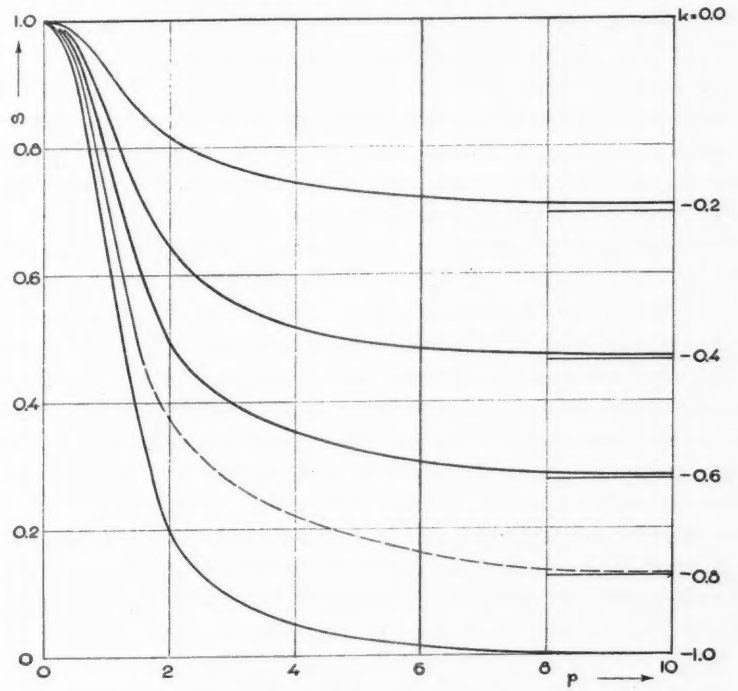

FIG. 14. Apparent resistivity curves for a dip angle $\alpha=22.5°$ at constant values of the reflection factor $0>k>-1$.

In case A of Figure 15, a relatively thin horizontal layer of the resistivity ρ_a is shown over a layer ρ_b and the dipping bed ρ_c underneath. As long as the depth of the dipping interface (b, c) is large enough in relation to the thickness (a) of the top layer and the intersection line of the dipping interface with the ground

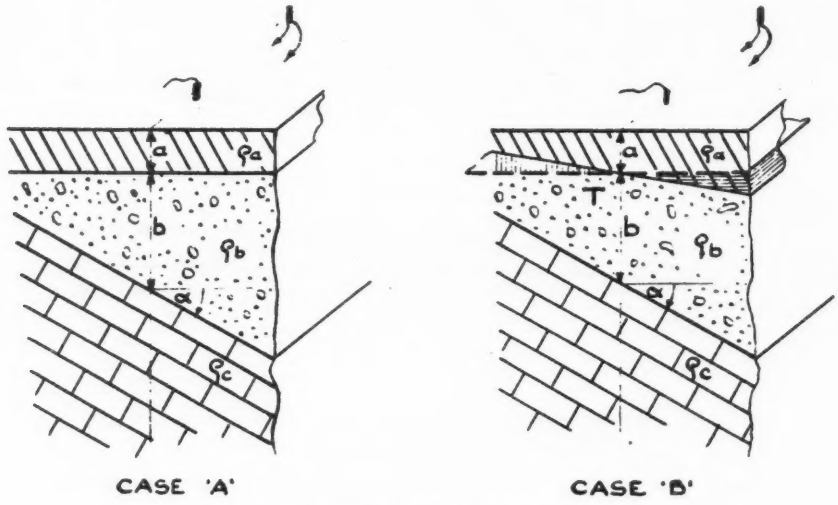

FIG. 15. Approximation of three layer problems.

surface runs beyond the detectable current field of the set-up, the conditions are the same as for parallel layers. The equivalent value ρ_{ab} for the two upper layers calculated under the assumption of parallel current paths at the ground surface in between the probes, is obtained in the usual way.

In case B of Figure 15 a relatively thin layer of resistivity ρ_a lies over two dipping layers ρ_b and ρ_c. Here it has first to be considered whether the approximation for parallel current paths is applicable.

As the interface (a, b) is supposed to be located far above the boundary plane (b, c), the current distribution at the ground surface will hardly affect the field of the bottom layer. We are only interested in the total amount of current flowing through the ρ_a, ρ_b zone, and not in the actual current distribution. By drawing an imaginary horizontal plane, as indicated by the dotted line through point T, two sectors are created in accordance with the overlap of the current loading. Upon replacing these two sectors the case is reduced to the example A discussed above.

When a and b denote the thicknesses of the top layers under the set-up axis, the composite resistivity according to Kirchhoff's law for parallel current paths amounts to

$$\frac{1}{\rho_{ab}} = \frac{1}{a+b}\left(\frac{a}{\rho_a} + \frac{b}{\rho_b}\right). \tag{24}$$

The approximation is considered permissible when the thickness of the third

layer exceeds that of the two top layers. The intersection lines of the dipping interfaces with the ground surface shall be not less than half the total electrode spread away from the set-up axis.

By successive grouping of the upper layers the method can be extended to any number of dipping beds.

D. METHOD OF INVESTIGATION

1. Field Procedure

As the variable $p=g/t$ of the potential function includes the probe distance as well as the depth of the dipping layer, surveys can be carried out by varying either of the two parameters. The electrode spacing is successively increased at a fixed station or the station is moved with the same set-up over the dip line of the inclined bed. In the latter case the set-up axis shall remain at all time parallel to the strike.

Which of the two methods is preferable will depend on the structural features of the location. For the elimination of surface effects the variation of the electrode spread along a fixed axis may prove more economical, whereas moving the set-up at right angles to the strike may often be easier for topographical reasons.

The approximate direction of the strike and a rough estimate of the dip angle are obtainable from the reconnaissance survey. In the case of small dip angles, up to 10 or 15 degrees, it will be sufficient to carry on the investigation by a series of depth determinations over the dip line, without regard to the effect of the inclined layers on the apparent resistivity values. For larger dip angles the new diagrams must be used.

The effects of anisotropy in the ground have to be considered in practice, particularly in the case of inclined beds when differently directed anisotropy factors may considerably distort the results. In view of the large number of parameters already involved in the calculations, it has been found that these effects are best treated by means of general correction factors, empirically obtained on the site.

Standard measuring equipment can be used for the field survey. A high degree of sensitivity will facilitate the interpretation, provided that a sufficient number of profiles is run to eliminate the errors from surface effects.

2. Interpretation of Results

The measured apparent resistivities are plotted over the probe distances and the curves thus obtained are matched with standard resistivity diagrams.

As soon as the value of the dip angle α is known, the survey curves can be correlated directly with the corresponding standard diagram for dipping layers, as has been done for horizontal beds. If the angle α is not given, a gradual process of approximation must be applied. The diagrams are checked for a number of survey stations over an estimated range of dip angles until coordination of the results is obtained.

3. *Example*

A two-layer case will be solved with the boundary plane dipping under $\alpha = 45$ degrees (Fig. 16). The underground has been assumed to be homogeneous and isotropic. Wenner set-ups, laid out parallel to the strike, are used.

The apparent resistivity curves obtained for two fixed stations A and B are shown in diagram 16 (2). All surface effects have been eliminated and the curves smoothed. The diagram has to be evaluated now by matching it with the standard $s = f(p)$ curves for $\alpha = 45°$ given in Figure 11.

This evaluation is best accomplished by the application of Roman's logarithmic method.* The diagrams to be compared are plotted in logarithmic scale and

* I. Roman, "Superposition in the Interpretation of Two-layer Earth Resistivity Curves," U.S.A. Dept. of the Interior, Geological Survey Bulletin 927-A; Washington (1941).

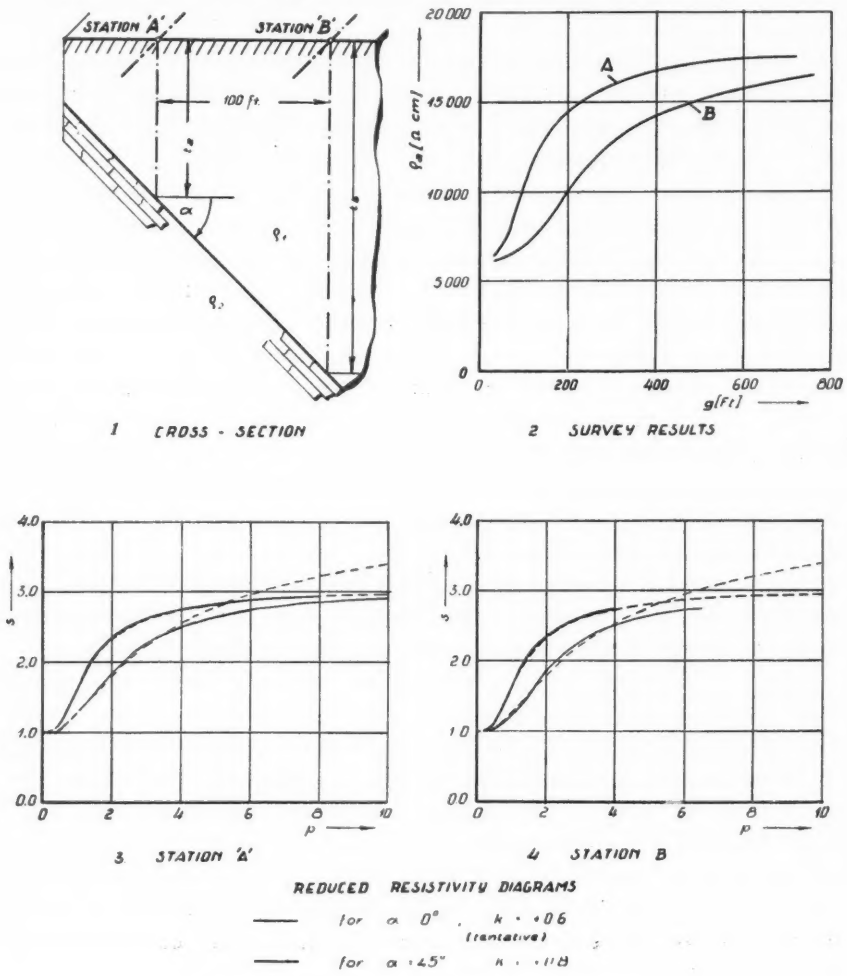

FIG. 16. Example of the method of interpretation.

superimposed upon each other. The reflection factor k is then given by the parameter of the corresponding standard curve, while the logarithmic values of ρ_1 and t are obtained from the differences between the coordinates. The following data are thus found for the two stations:

Reflection Factor k:	+0.8
Resistivity ρ_1	6,000 Ωcm
Resistivity ρ_2	54,000 Ωcm
Depth t_a	90 ft
Depth t_b	190 ft

The reduced resistivities for stations A and B are obtained by dividing the apparent resistivities of Figure 16 (2) by the respective values of ρ_1 and t. In order to check the results these reduced resistivities are plotted in the linear diagrams 16 (3) and (4) with the standard $s=f(p)$ lines shown dotted.

If the dip angle α of the boundary plane were not known, the apparent resistivity curves of Figure 16 (2) would have to be tentatively matched with the standard diagrams for various dips. The error involved in such random geometrical matching is illustrated by the alternative curves of Figure 16 (3) and (4), where an attempt was made with the known diagram for horizontal beds. As could be expected from the divergence of the curves at higher p, the constants obtained this time were different:

$$k' = +0.6; \qquad \rho_1 = 6{,}000\ \Omega\text{cm};$$
$$t_a' = 55\ \text{ft.}; \qquad t_b' = 117\ \text{ft.};$$
$$\alpha' = 32°.$$

By referring to higher standard sets of curves, say for $\alpha=36°$ and 45°, the correct solution could be found.

E. CONCLUSIONS

A link has been established in the theory of resistivity surveys between the known solution for horizontal layers and that for the vertical fault.

Exact diagrams have been obtained for the reflection factors $k=\pm 1$, and a practically sufficient approximation for most of the other values of k.

The diagrams are of the same type as those published for horizontal layers and can be applied to the interpretation of survey results in the usual way.

The method is of particular interest for surveys in deeply eroded or faulted country.

ACKNOWLEDGEMENT

The author wishes to express his thanks to Prof. F. Ollendorff, Principal of the Electrotechnical Institute at the Technical College, Haifa, for the keen interest he took in reading the manuscript of the paper, and for all his valuable advice.

TRANSIENT COUPLING IN GROUNDED CIRCUITS*

JAMES R. WAIT†

ABSTRACT

Transient coupling between insulated circuits of finite length grounded at their end points in an infinite homogeneous and conducting medium is investigated. The general result is specialized to the case of a typical electrodal array as used in electrical resistivity logging in wells or drill holes. A graphical example shows how the voltages build up to their static value due to a suddenly applied current.

INTRODUCTION‡

In certain problems of electrical resistivity logging in wells, commutated direct currents are often used. It is then of considerable interest to know exactly how a homogeneous conducting medium will react to a current suddenly applied to two grounded electrodes at a specified separation in a well. In particular, it is desirable to know how the resulting voltage between two additional grounded electrodes, also within the well, builds up to its static value following the application of the current. The transient voltage response in one finite grounded circuit due to a step function current in another similar circuit, which is itself parallel to the first, will be calculated. A special case of this general result will be then studied in more detail.

THE TRANSIENT CALCULATION

A circuit consisting of an insulated wire is embedded in an infinite and isotropic medium with a conductivity σ and magnetic permeability μ. The wire is grounded at the points A and B, which are shown in Figure 1.

By some means a unit step-function current is caused to flow in the wire throughout its length. The electric field at the point P of co-ordinates (ρ, z) was given previously by the author for this situation. The z component of the electric field $E_z(t)$ is:

$$E_z(t) = (\mu/8\pi t) \exp(-\beta^2\rho^2)\{\operatorname{erf}[\beta(B-z)] - \operatorname{erf}[\beta(A-z)]\} + (1/4\pi\sigma)[M(r_1) - M(r_2)] \tag{1}$$

where

$$M(r) = (z-S)/r^3[1 - \operatorname{erf}(\beta r) + \beta r \operatorname{erf}'(\beta r)],$$

$$r_1 = [(A-z)^2 + \rho^2]^{1/2}, \qquad r_2 = [(B-z)^2 + \rho^2]^{1/2},$$

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‡ The analysis in this paper is a direct extension to that in a previous paper by the author in GEOPHYSICS XVI, 2 (1951), 213.

and

$$\beta = (\sigma\mu/4t)^{1/2},$$

where the notation is as in the previous paper (1). The open-circuit voltage, $v(t)$, will now be calculated, that is induced in a finite insulated circuit, grounded at

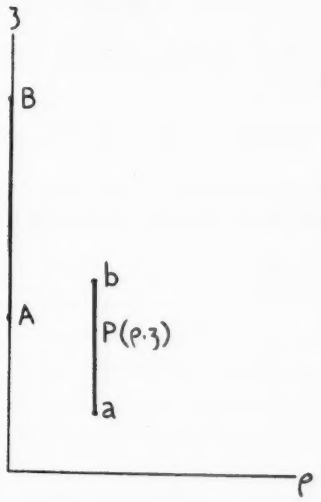

FIG. 1. The coordinate system for two parallel wires grounded at their end points in a conducting medium of infinite extent.

the points a and b, and separated from the first circuit by a constant separation ρ then:

$$v(t) = \int_a^b E_z(t)dz. \tag{2}$$

This can be rewritten in the following form:

$$v(t) = (1/4\pi\sigma)\int_a^b \frac{\partial}{\partial z}\left[\frac{\operatorname{erfc}(\beta r_2)}{r_2} - \frac{\operatorname{erfc}(\beta r_1)}{r_1}\right]dz$$

$$+ (\mu/8\pi t)\exp(-\beta^2\rho^2)\int_a^b \{\operatorname{erf}[\beta(B-z)] - \operatorname{erf}[\beta(A-z)]\}dz. \tag{3}$$

The following indefinite integral can be easily verified,

$$\beta\int \operatorname{erf}(\beta x)dx = \beta x \operatorname{erf}(\beta x) + \frac{\operatorname{erf}'(\beta x)}{2} = \psi(\beta x), \tag{4}$$

and this defines the function $4(\beta n)$. Employing this result, the required integrations can be carried out to yield:

$$v(t) = 1/4\pi\sigma\left[\frac{\operatorname{erfc}\,[\beta B\cdot b]}{B\cdot b}+\frac{\operatorname{erfc}\,[\beta A\cdot a]}{A\cdot a}-\frac{\operatorname{erfc}\,(\beta B\cdot a)}{B\cdot a}-\frac{\operatorname{erfc}\,(\beta A\cdot b)}{A\cdot b}\right]$$
$$+\frac{1}{4\pi}\left(\frac{\mu}{\sigma t}\right)^{1/2}\exp\,(-\beta^2\rho^2)\,[\psi[\beta(B-a)]+\psi[\beta(A-b)]$$
$$-\psi[\beta(A-a)]-\psi[\beta(B-b)]], \qquad (5)$$

where the dot between the points signifies a linear dimension equal to the actual separation of the points. That is,

$$B\cdot b = [\rho^2+(B-b)^2]^{1/2}, \text{ etc.}$$

The above rather complicated expression will give the open circuit voltage, in volts, in the circuit ba to suddenly applied current of one ampere applied to the

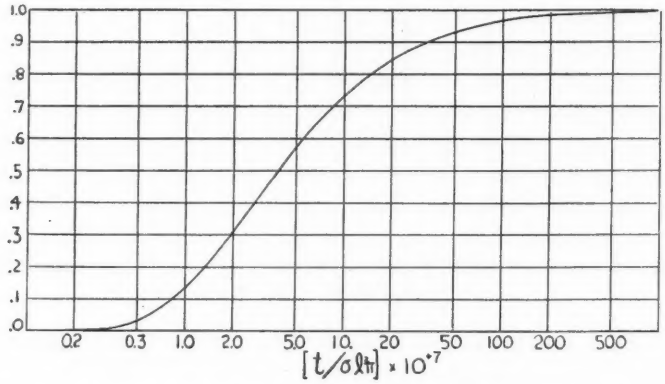

FIG. 2. The build-up of the voltage due to a suddenly applied current for a special type of resistivity electrode array in a drill hole or well.

circuit BA which is parallel and at a separation ρ. The response $V(t)$ in the circuit ba to current applied at $t=0$ of arbitrary form $R(t)$ is then given formally in terms of $v(t)$ by the superposition integral for step-functions (2).

$$V(t) = \frac{d}{dt}\int_0^t v(t-\tau)R(\tau)d\tau$$
$$= \frac{d}{dt}\int_0^t R(t-\tau)v(\tau)d\tau. \qquad (6)$$

When $v(t)$ is thus known, the responses to some other type of waveform, such as a rectangular current pulse can be readily computed.

A SPECIAL CASE

A common electrode array used in resistivity prospecting in wells or drill

holes is the three electrode collinear array of equal spacings. This is represented by the following special case of the general formulation:

$$B = +\infty, \quad A - a = 2l, \quad A - b = l \quad \text{and} \quad \rho = 0.$$

The current line in this case is assumed to act in an equivalent manner as a semi-infinite wire. This is effected by positioning the electrode B at a sufficiently great distance from the other electrodes. The voltage developed in the circuit ba is then measured by a high impedance voltmeter. The voltage $v(t)$ corresponding to this case, is given by:

$$-8\pi\sigma l \cdot v(t) = 2\,\mathrm{erfc}\,(\beta l) - \mathrm{erfc}\,(2\beta l) - 4\beta^2 l^2[1 + (4(\beta l) - 4(2\beta l))/\beta l]. \quad (7)$$

The quantity on the right hand side of this equation is then plotted in Figure 2 as a function of the parameter $t/\sigma l^2\pi$ where t is the response time in seconds, l is the electrode spacing in meters, and σ is the conductivity in mhos per meter. This quantity approaches the value one for long times and represents the static condition of current flow.

ACKNOWLEDGMENT

The author would like to thank Dr. A. A. Brant and Dr. H. O. Seigel of Newmont Exploration Ltd. for their interest and suggestions during the course of this work.

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THE SEISMIC HISTORY OF SOUTHEASTERN NEW MEXICO*

ARLAND I. INNES†

ABSTRACT

Seismic exploration in southeastern New Mexico was initiated early in 1928 by the Amerada Petroleum Corporation and the Gulf Oil Company. In the period 1928–1931, refraction profiling was exclusively used to detail Hobbs and to locate the Monument structure. The 1932–1935 period was dominated by correlation refractions. Detailed shooting outlined the Monument structure. During the period 1934–1950, reflection profiling was successfully used and is credited with locating the Knowles, Bagley, Hightower, Cross Roads, Denton, Bough, and Saunders oil fields.

The presentation of data includes reproductions of seismic records and structure maps.

INTRODUCTION

There has been seismic activity in southeastern New Mexico ever since 1928. The climax of the early work was the discovery of the Monument field early in 1935. During 1949 and 1950 there were nine discoveries in the area in and around Lea, Chaves, and Roosevelt Counties. Figure 1 shows the Northwestern Shelf Area of the West Texas Permian Basin and the location of Knowles, Bagley, Hightower, Cross Roads, Denton, Bough, Saunders, Lightcap, and Gladioli oil fields. The first six of these discoveries were officially credited to the seismograph in the A.A.P.G. bulletin for June 1950, and there is reason to believe that the last three were also drilled on seismic information.

The purpose of this paper is to trace the seismic development in Southeastern New Mexico from 1928 through 1950. The history may be divided into three periods which are characterized by different seismic techniques: 1928–1931 Refraction Profiling, 1932–1935 Correlation Refractions, and 1934–1950 Reflection Profiling.

PART ONE—1928–1931—REFRACTION PROFILING

Prior to 1928 geophysical activity in the northwestern part of the Central Basin Platform of the West Texas Permian Basin had been confined to magnetic and torsion balance surveys. The discovery of oil at Hobbs and gas in several wells south of Hobbs created interest in Southeastern New Mexico. Early in 1928 two Geophysical Research Corporation seismograph crews were moved into the area by Gulf and Amerada to determine if the seismograph could map subsurface structure. Dynamite charges were shot on the surface as it was impossible to dig holes with hand augers in the hard sandstone and caliche that is found on the surface in this area. Profiles were shot continuously from zero to twenty

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† Amerada Petroleum Corporation, Tulsa, Oklahoma.

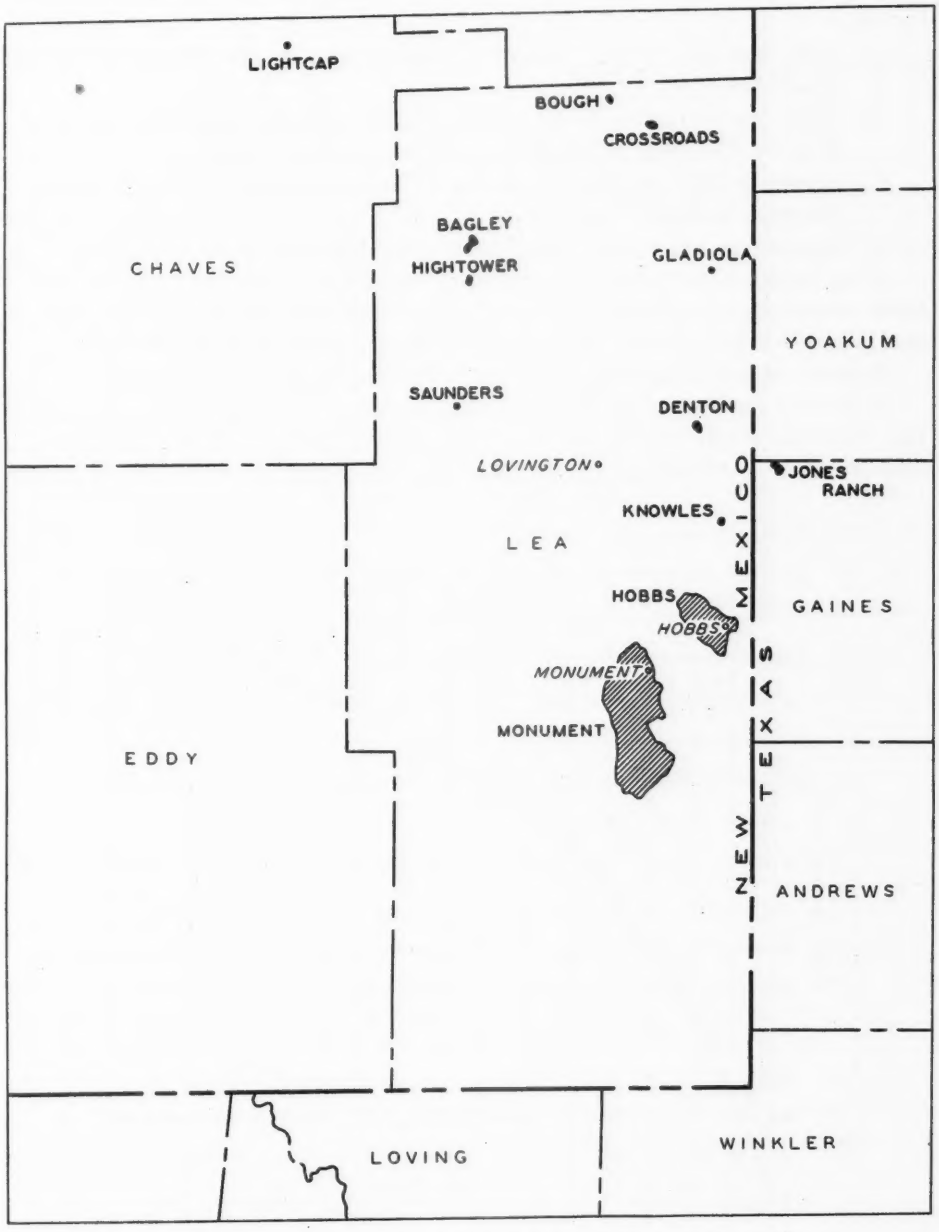

FIG. 1. Index map of southeastern New Mexico and West Texas showing discoveries in 1949 and 1950.

thousand feet. The following velocities were secured from the time distance curves.

(a) 4,000 feet per second—A slow speed material at the surface called the weathered layer.

(b) 7,000 feet per second—A higher velocity material near the top of the Triassic Red Beds referred to as the unweathered layer.

(c) 10,000 feet per second—Probably a hard sandstone near the Triassic-Permian Red Bed Contact.

(d) 18,300 feet per second—A high speed material assumed to be lime.

First breaks which were expected from the salt and anhydrite section would have determined a velocity between (c) and (d), but the high absorption of energy in the salt and anhydrite prevented the recording of usable breaks.

Figure 2 shows a time distance curve that was typical for the area.

A method for computing the refraction profiles was set up on the assumption that the waves traveled in straight lines. A multiple layer depth computation was made using the intercept or delay times. The first step peeled off the weath-

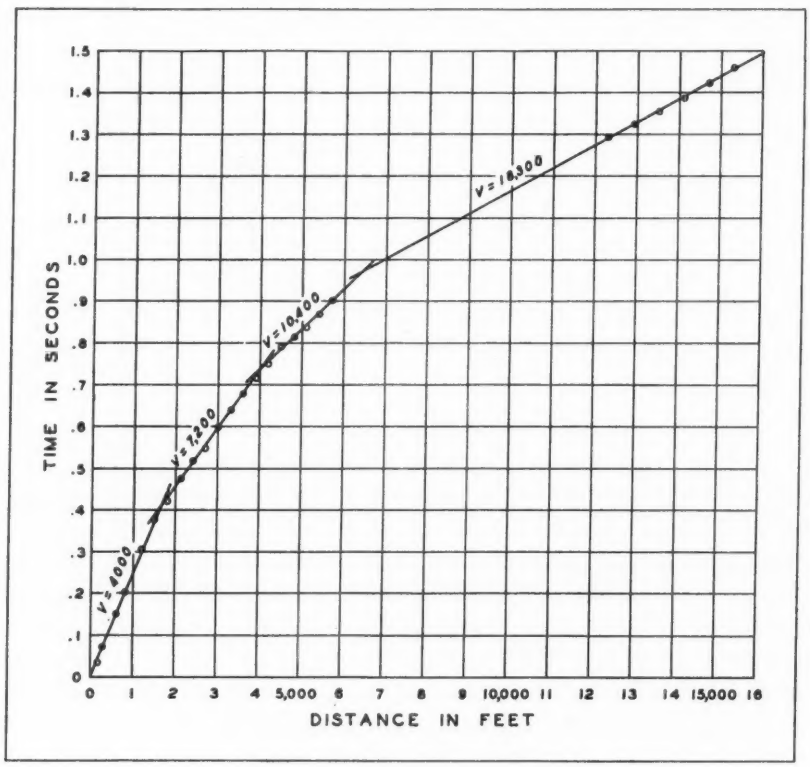

FIG. 2. Time distance curve for refraction profile in southeastern New Mexico, 1928.

DATE SHOT
SEC. 16 TWP. 17S RANGE 36E
LOCATION S. P. S.E. Cor.
DIRECTION SHOT North

G R C TROOP No. 311
CHIEF
STATE New Mexico
COUNTY Lee

POSITION No. 227
COMPUTED
COMPUTER
ELEVATION S. P. 3888

		FIRST LAYER	FIFTH LAYER
U_1 4000	U_1/V_2 = SIN∝12 = .5479 12 = 33.22 TAN∝12 = .6549	$G_{12} = \frac{V_2C_2}{2}$ = 99	$F_{16} = H_1 \cot \propto_{16}$ =
U_2 7000		$H_1 = G_{12} \tan \propto_{12}$ = 65	$F_{26} = H_2 \cot \propto_{26}$ =
U_3 11.000	U_1/V_3 = SIN∝13 = .3883 13 = 22.85 COT∝13 = 2.3731	$D_1 = E - H_1$ = 3823	$F_{36} = H_3 \cot \propto_{36}$ =
U_4 13,500	U_2/V_3 = SIN∝23 = .6796 23 = 42.82 TAN∝23 = .9266	$X_1 = H_1 \tan \propto_{12}$ = 43	$F_{46} = H_4 \cot \propto_{46}$ =
U_5			$J_{56} = \frac{V_5C_5}{2}$ =
U_6	U_1/V_4 = SIN∝14 = .2299 14 = 13.30 COT∝14 = 4.230	SECOND LAYER	$H_5 = G_{56} - F_{16} - F_{26} - F_{36} - F_{46} \tan \propto_{56}$ =
U_7	U_2/V_4 = SIN∝24 = .4023 24 = 23.72 COT∝24 = 2.276	$F_{13} = H_1 \cot \propto_{13}$ = 154	$D_5 = 4D - H_5$ =
	U_3/V_4 = SIN∝34 = .7759 34 = 50.89 TAN∝34 = 1.2301	$G_{23} = \frac{V_3C_3}{2}$ = 608	$X_5 = \frac{H_1\tan\propto_{15} + H_2\tan\propto_{25} + H_3\tan\propto_{35} + H_4\tan\propto_{45} + H_5\tan\propto_{56}}{}$ =
V_1 4000		$H_2 = G_{23} - F_{13} \tan \propto_{23}$ = 421	SIXTH LAYER
V_2 7300	U_1/V_5 = SIN∝15 = 15 = COT∝15 =	$D_2 = D_1 - H_2$ = 3402	
V_3 10.300	U_2/V_5 = SIN∝25 = 25 = COT∝25 =	$X_2 = H_1 \tan \propto_{13} + H_2 \tan \propto_{23}$ = 417	$F_{17} = H_1 \cot \propto_{17}$ =
V_4 17.400	U_3/V_5 = SIN∝35 = 35 = COT∝35 =	THIRD LAYER	$F_{27} = H_2 \cot \propto_{27}$ =
V_5	U_4/V_5 = SIN∝45 = 45 = TAN∝45 =	$F_{16} = H_1 \cot \propto_{16}$ = 275	$F_{37} = H_3 \cot \propto_{37}$ =
V_6		$F_{26} = H_2 \cot \propto_{26}$ = 958	$F_{47} = H_4 \cot \propto_{47}$ =
V_7	U_1/V_6 = SIN∝16 = 16 = COT∝16 =	$G_{36} = \frac{V_6C_6}{2}$ = 4367	$F_{57} = H_5 \cot \propto_{57}$ =
	U_2/V_6 = SIN∝26 = 26 = COT∝26 =	$H_3 = G_{36} - F_{16} - F_{26} \tan \propto_{36}$ = 3855	$G_{67} = \frac{V_7C_7}{2}$ =
C_1 .000	U_3/V_6 = SIN∝36 = 36 = COT∝36 =	$D_3 = D_2 - H_3$ = -453	$H_6 = G_{67} - F_{17} - F_{27} - F_{37} - F_{47} - F_{57} \tan \propto_{67}$ =
C_2 .027	U_4/V_6 = SIN∝46 = 46 = COT∝46 =	$X_3 = \frac{H_1\tan\propto_{14} + H_2\tan\propto_{24} + H_3\tan\propto_{34}}{}$ = 4942	$D_6 = D_5 - H_6$ =
C_3 .118	U_5/V_6 = SIN∝56 = 56 = TAN∝56 =	FOURTH LAYER	$X_6 = \frac{H_1\tan\propto_{17} + H_2\tan\propto_{27} + H_3\tan\propto_{37} + H_4\tan\propto_{47} + H_5\tan\propto_{57} + H_6\tan\propto_{67}}{}$ =
C_4 .502		$F_{15} = H_1 \cot \propto_{15}$ =	
C_5	U_1/V_7 = SIN∝17 = 17 = COT∝17 =	$F_{25} = H_2 \cot \propto_{25}$ =	DATUM
C_6	U_2/V_7 = SIN∝27 = 27 = COT∝27 =	$F_{35} = H_3 \cot \propto_{35}$ =	TOP OF Unweathered = 3823
C_7	U_3/V_7 = SIN∝37 = 37 = COT∝37 =	$G_{45} = \frac{V_5C_5}{2}$ =	TOP OF Red Bed = 3402
	U_4/V_7 = SIN∝47 = 47 = COT∝47 =	$H_4 = G_{45} - F_{15} - F_{25} - F_{35} \tan \propto_{45}$ =	TOP OF Lime = -453
	U_5/V_7 = SIN∝57 = 57 = COT∝57 =	$D_4 = D_3 - H_4$ =	TOP OF =
	U_6/V_7 = SIN∝67 = 67 = TAN∝67 =	$X_4 = \frac{H_1\tan\propto_{15} + H_2\tan\propto_{25} + H_3\tan\propto_{35} + H_4\tan\propto_{45}}{}$ =	TOP OF =
			TOP OF =

FIG. 3. Computation form for layer by layer method of depth determination from refraction profile, 1929.

ered layer and the second step peeled off the unweathered layer. The third step in the computation grouped the remainder of the red beds, salt, and anhydrite into a single layer. Profiles were shot across several wells to determine the average vertical velocity for this layer. A velocity of 13,500 feet per second checked the lime depths reasonably well. A copy of a calculation sheet used by these crews is shown in Figure 3. U_1, U_2, U_3, and U_4 are the assumed vertical velocities. V_1, V_2, V_3, and V_4 are the velocities obtained from the time distance curve. C_1, C_2, C_3, and C_4 are the intercepts or delay times from the same curve. The next column to the right evaluates the sines, tangents, and cotangents of the various angles. The third and fourth columns give the depth and mirage distance for each layer. The datum for each layer is tabulated in the lower right-hand corner.

The results of this experimental work indicated clearly that refraction profiles could be successfully used to map subsurface structure in the area. Reconnaissance work was started immediately and within six months five crews were shooting in southeastern New Mexico and adjoining areas of West Texas.

The work done by these crews would be considered crude and inaccurate by

comparison with present day standards. Permits, then as now, were difficult to secure so wherever a permit was obtained, a profile was shot. The surveyor used an alidade or altimeter to run the elevations, and detector stations were set by automobile speedometer. The horizontal distances from shot point to recording stations were computed from air blast times. Dynamite charges of 700 to 800 pounds per shot were the rule for the longest shots on the profiles. It was rare for a crew to average more than one profile per day. Four profiles per township were considered adequate coverage and six to eight profiles in a township constituted good coverage.

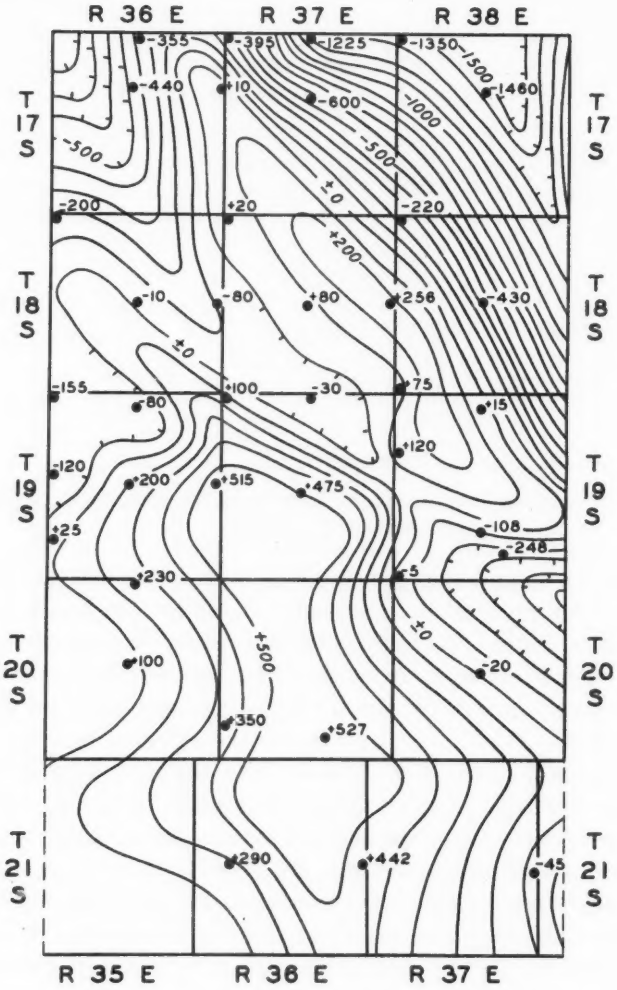

FIG. 4. Structure map of southeastern New Mexico contoured on top of lime as determined by refraction profiles, 1929. Contour interval 100 feet. The +200 closure outlines Hobbs and the +500 closure outlines Monument.

One wonders today how such a program could map the subsurface structure because it falls so far short of what is now considered a minimum amount of work. Yet, with all their deficiencies, the refraction maps showed well defined structures. Figure 4 shows an Amerada Petroleum Corporation refraction map that was contoured in April, 1929, on which the Hobbs and Monument structures are clearly indicated. The +200 closed contour outlines the Hobbs structure and the +500 closure in the south part defines the productive limit of the Monument field. The density of data on and around these structures indicates an unusual amount of shooting for those days. Twenty depths were necessary to detail them!

The work of an Amerada crew with headquarters at Lovington in November,

SHOT NO.	DISTANCE IN FEET	DYN. LBS. IN DEEP HOLES	DYN. LBS. AVE. FOR 6 SURFACE SHOT POINTS
1	400-1600	1/4	30
2	2000-3200	1/4	60
3	3600-4800	5	60
4	11,000-12,800	20	450
5	13,400-15,200	150	600
6	15,800-17,600	50	800
TOTALS		225.5	2000

FIG. 5. Comparison of charges in deep holes and from surface shots for same spread distance on refraction profiles, 1929.

1929 is important because it was the first one to use deep holes anywhere. The ranchers had been claiming that the noise created by surface shooting was causing their cattle "to run the fence" which made them lose an appreciable amount of weight. The claim was justified and it threatened to put an end to refraction shooting. The answer was deep holes, but how to obtain them was a real problem. The Party Chief at Lovington had watched a portable spudder digging a water well for a rancher and suggested that this machine might be used to dig deep holes. The first experimental holes were dug eighty feet to the water table using an eight inch bit. They proved to be a success for dynamite charges dropped sharply and the record quality was materially improved by increased amplitude of the first breaks.

Figure 5 shows a comparison of dynamite charges between shooting in deep holes at one shot point and the average charge for shooting on the surface for six shot points for detector stations at the same spread distance. The irregular increase in charge on shot number five in the deep hole was caused by caving. The reduction in charges was typical of all deep holes.

It was impossible to make reproductions of the early seismic records, but

exact tracings have been prepared in Figure 6 which shows records shot on the surface. These may be compared with records of comparable distances shot in deep holes in Figure 7. The advantage in favor of deep holes is obvious.

The success of the experimental deep holes was exploited immediately. Deep hole drilling was placed on a production basis. The diameter of the hole was gradually reduced from eight to four inches. Damage claims were reduced to a minimum and permits were easier to secure. Henceforth, seismic units operating

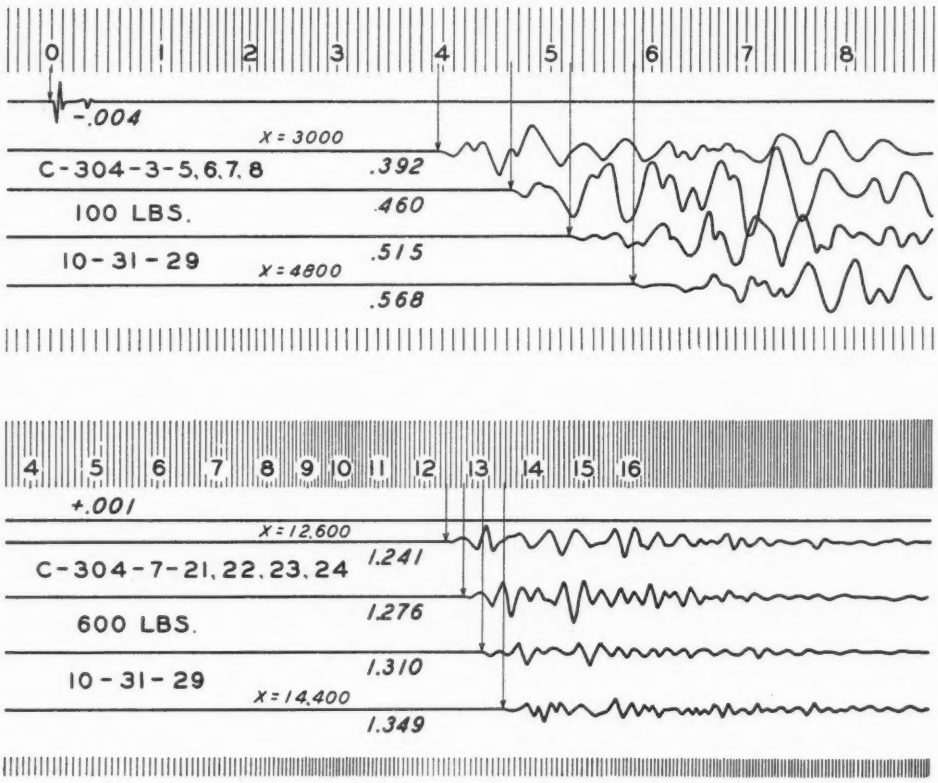

FIG. 6. Records from surface shots, 1929.

on the Central Basin Platform of the West Texas Permian Basin had from one to three spudders assigned to them.

As refraction shooting around Lovington progressed and several wildcats were completed, serious discrepancies between the geological and seismic depths appeared. In one case, the total error was 1,700 feet where the seismic depths showed a well 1,350 feet *down* dip from another well, whereas the geological control showed 350 of dip in the *opposite* direction. Well logs were studied to determine the geological changes that had taken place. The thickness of each bed was noted on a map at well locations and these data were contoured. The map showed the

red beds thickened and the salt thinned northeast from the Monument structure. The anhydrite section thickened or thinned irregularly. In using a constant velocity over the area, it had been assumed that the geological section remained constant or that any changes compensated each other. It was apparent that the increase in red bed thickness and the decrease in salt thickness had caused the vertical velocity to be in error because 1,000 feet of red beds, 1,500 feet of salt

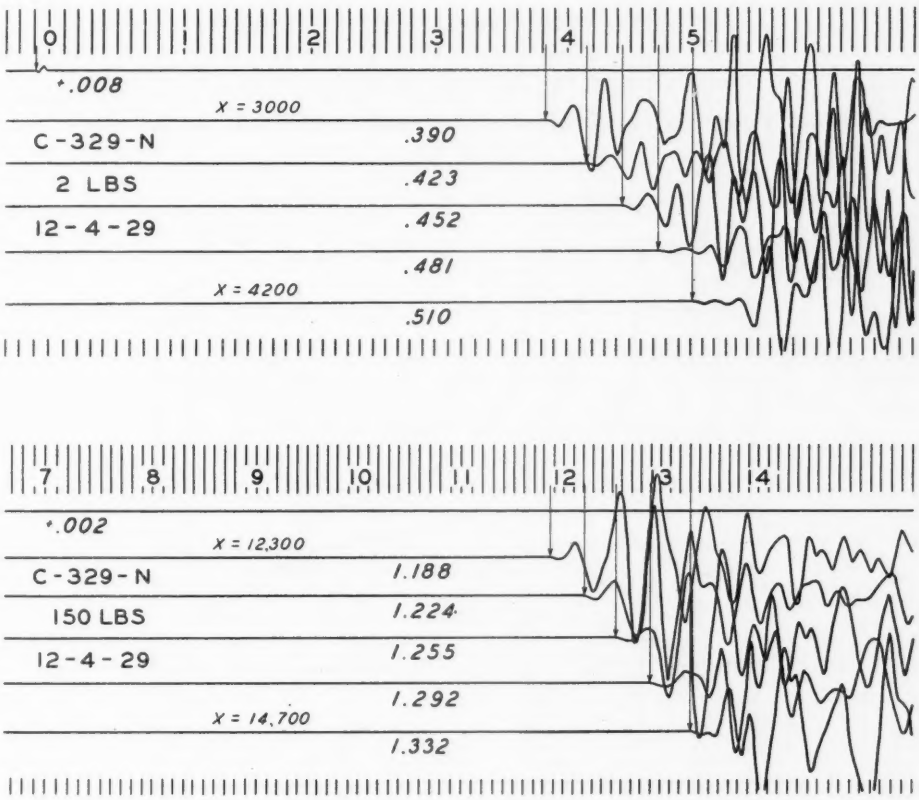

FIG. 7. Records from deep holes, 1929.

and 1,500 feet of anhydrite had been grouped into one layer. The remedy was to measure the actual velocities of each part of the section and combine them according to the measured thickness in all available wells. The velocities were measured in a velocity survey of the Buell and Hagen #1 State well located in Section 33, Township 11 South, Range 35 East, Lea County. The average vertical velocities were computed according to the formula in Figure 8 for all wells covered by the refraction survey. These average velocities were posted on a map and iso-velocity lines were drawn conforming to the geological trend, as it was then thought to be. This map is shown in Figure 9. Probably this was the first iso-

$$\bar{T} = \frac{R}{VR} + \frac{S}{VS} + \frac{A}{VA} \quad \text{AND} \quad \bar{V} = \frac{R+S+A}{T}$$

$\bar{T}$ = AVERAGE TIME
R = THICKNESS OF RED BEDS
S = THICKNESS OF SALT
A = THICKNESS OF ANHYDRITE
$\bar{V}$ = AVERAGE VERTICAL VELOCITY
VR = VERTICAL VELOCITY OF RED BEDS
VS = VERTICAL VELOCITY OF SALT
VA = VERTICAL VELOCITY OF ANHYDRITE

FIG. 8. Formula for average vertical velocity through red bed, salt, and anhydrite section, 1930.

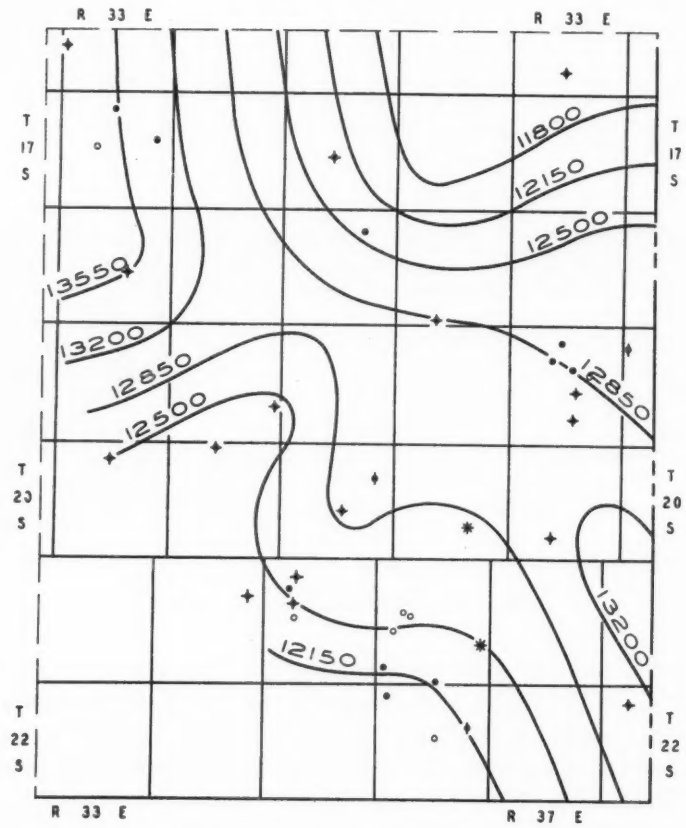

FIG. 9. Iso-velocity map of southeastern New Mexico, 1930. Average vertical velocities were computed by formula in Figure 8 for all wells shown. Contour interval 350 feet per second.

velocity map made in the West Texas Permian Basin. It suffered from the same fault that all velocity maps have, for each new well can materially change the contours of such a map.

New depth computations were made using a velocity for each profile according to the iso-velocity map. The new depths reduced the apparent relief on the Hobbs and Monument structures as shown in Figure 10. On Figure 10, Hobbs in

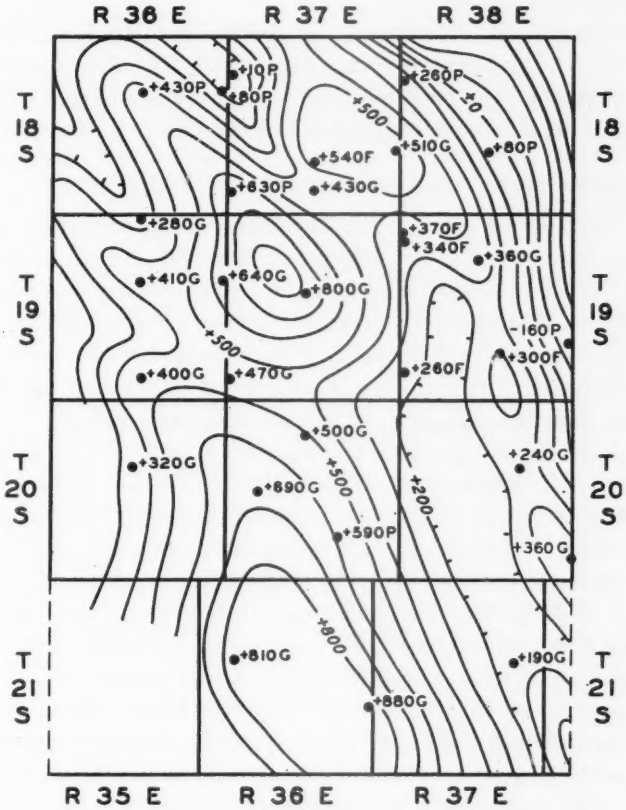

FIG. 10. Structure map of southeastern New Mexico contoured on top of lime with depths from refraction profiles corrected according to velocity control on Figure 9, 1930.

T-18S, R-37E is not so well defined as on Figure 4, and Monument in T-19 and 20S, R-37E is split into a small structure on the north and a nosing from the southeast. There is insufficient control to close the nose on the south.

The results of the 1928–1931 period of refraction profiling were:

(a) The northwest part of the Central Basin Platform of the West Texas Permian Basin had been opened to the seismograph.

(b) Structural features could be found if they were of sufficient size to show appreciable refraction time differences, and they could be detailed to a limited degree.

(c) The multiple layer method of calculating depths had been developed and used successfully.
(d) Deep machine dug holes became standard practice.
(e) Velocity surveys which were in an experimental stage had been shot successfully at the Marland #1 Reed and the Buell and Hagen #1 State wells in Lea County, New Mexico, and the Deep Rock #1 Harris well in Andrews County, Texas.

Credit for the success of this work should be given to J. C. Karcher, E. E. Rosaire, and E. E. McDermott, who supervised the experimental refraction shooting and developed the multiple layer calculations, and to B. B. Weatherby who directed the deep hole experimentas and the velocity surveys.

PART TWO—1934–1935—CORRELATION REFRACTIONS

The 1932–1935 period marked the development of correlation refractions as a means to locate structures. A Geophysical Research Corporation crew moved to Lovington, New Mexico, in March, 1932, to experiment with second arrivals from the lime. The idea had been suggested by the work of another crew in 1930 which had as one of its problems—"To secure good first breaks from the salt." It was common practice at this time to pick second refraction arrivals as an aid in determining velocity. While shooting the salt part of the profile the Party Chief noted a high amplitude break immediately after the low frequency and low amplitude salt break. When plotted on the time-distance curve, this break fell on the lime velocity line established by positions taken further out on the profile. It occurred to him that both salt and lime points could be secured on the same set up if the frequency characteristics of the detector circuit were adjusted to minimize the low frequency salt break and to emphasize the higher frequency lime break. In order to evaluate this method further, the crew at Lovington checked the Hobbs anticline which was now fully developed, and then reaffirmed the undrilled structure at Monument which had been indicated by refraction profiles. The party found that using small dynamite charges ranging from two to twenty-five pounds of powder was the secret in securing the sought for lime breaks, rather than adjustment of the frequency characteristics of the recording circuit. It was also noted that these lime breaks could be correlated from shot point to shot point and that one detector set up per profile was adequate for correlation purposes. Figure 11 shows typical records of correlation refractions. The top record was taken near the top of the Monument structure; the bottom record was taken on the northwest flank of the same structure and the middle record at an intermediate position. At this recording distance the salt refraction breaks would normally be the first breaks and would be expected several hundredths of a second earlier than the lime breaks that are marked on the records. The whole process suggested a rapid exploration technique. However, it was not until November, 1933, that an Amerada Petroleum Corporation crew began shooting correlation refractions on a production basis at Seminole, Texas. A

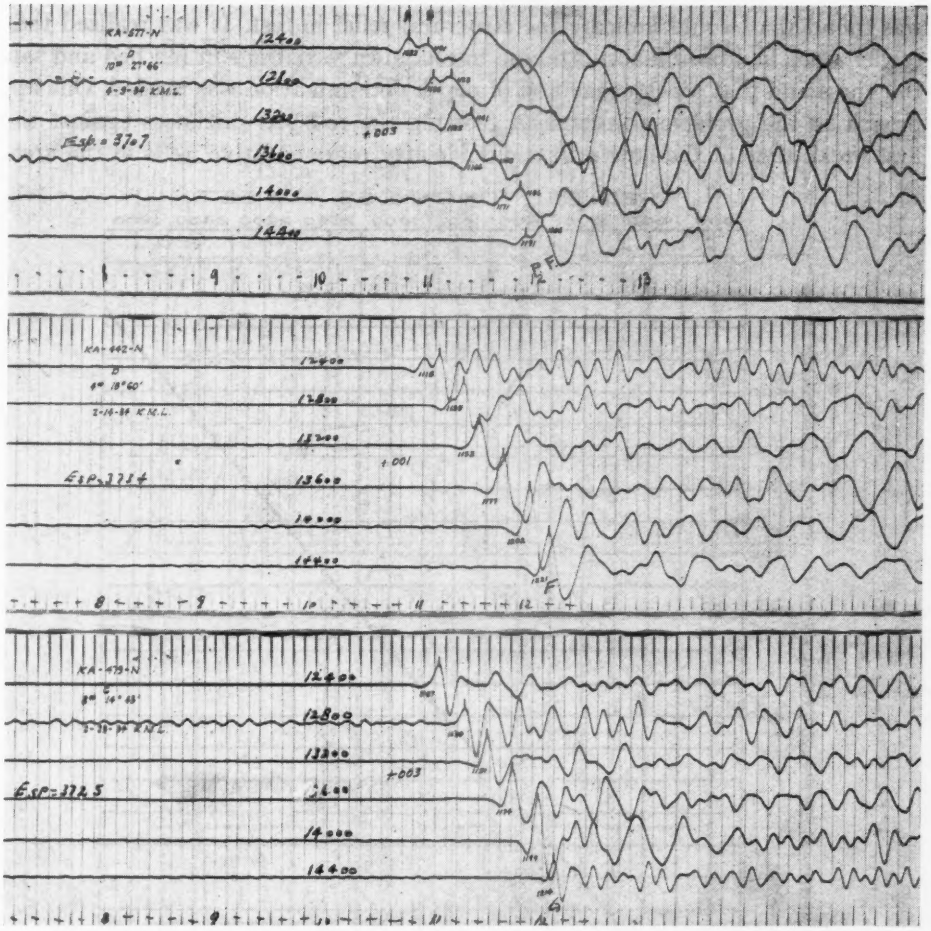

FIG. 11. Typical correlation refraction records, 1934. The top record was shot near the top of the Monument structure, the bottom record on the northwest flank, and the middle record at an intermediate position.

leasing play at Seminole and the staking of a wildcat at Monument attributed to the work of this Amerada crew created an unusual amount of interest in the seismic method as a possible tool to find structures in the West Texas Permian Basin. By late 1934 Shell, Sinclair, and Humble had moved seismic crews to Hobbs, New Mexico, and the Texas Company and Stanolind had seismic units at Carlsbad, New Mexico.

Field procedure for obtaining correlation refraction records was well established before a satisfactory method of computing depths was evolved to indicate the relief on structures. During this period maps were contoured on variations in time. Several false starts were made before a satisfactory method of computation

was found that would indicate the structural relief in feet. It was realized that earlier work had been inaccurate due to unknown variations in red bed and salt thickness and that a better method of depth determination was needed. One approach to the problem consisted of plotting the red bed thickness against the first break time of the lime refractions for fifty representative wells in the area.

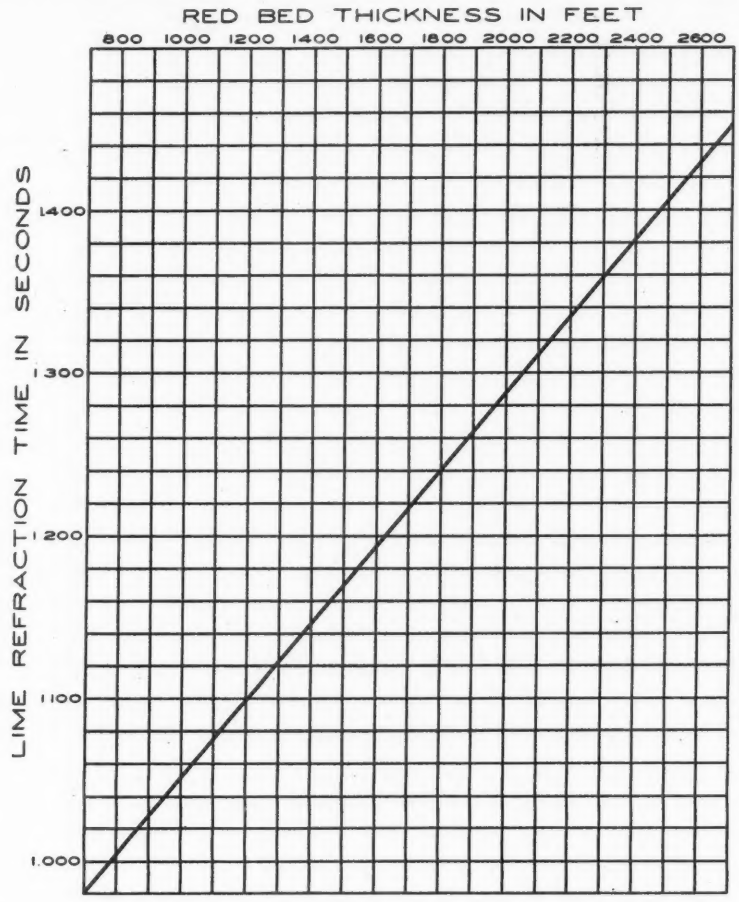

FIG. 12. Chart showing relation between thickness of red bed in wells and time of lime refractions, 1933.

A straight line fitted these points and Figure 12 shows this relation of red bed thickness versus lime refraction time. This curve was used in computing depths and the results proved to be very accurate. Figure 13 is a map of Monument contoured on top of the Rustler Anhydrite as determined by lime refractions. The contour interval on this map is one hundred feet. Figure 14 is a subsurface geological map of Monument contoured on the same horizon with a contour interval of fifty feet. The agreement is excellent.

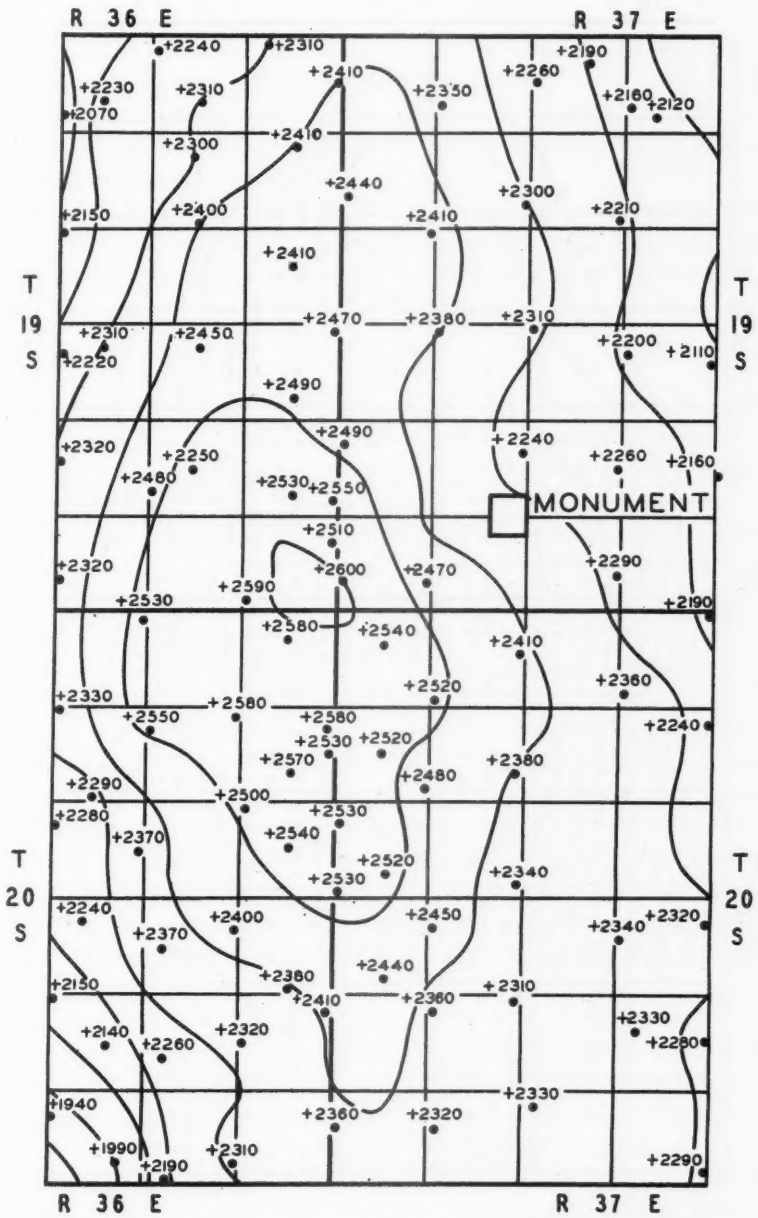

FIG. 13. Structure map of Monument area contoured on top of Rustler anhydrite using correlation refraction times and chart in Figure 12 for depths, 1934. Contour interval 100 feet.

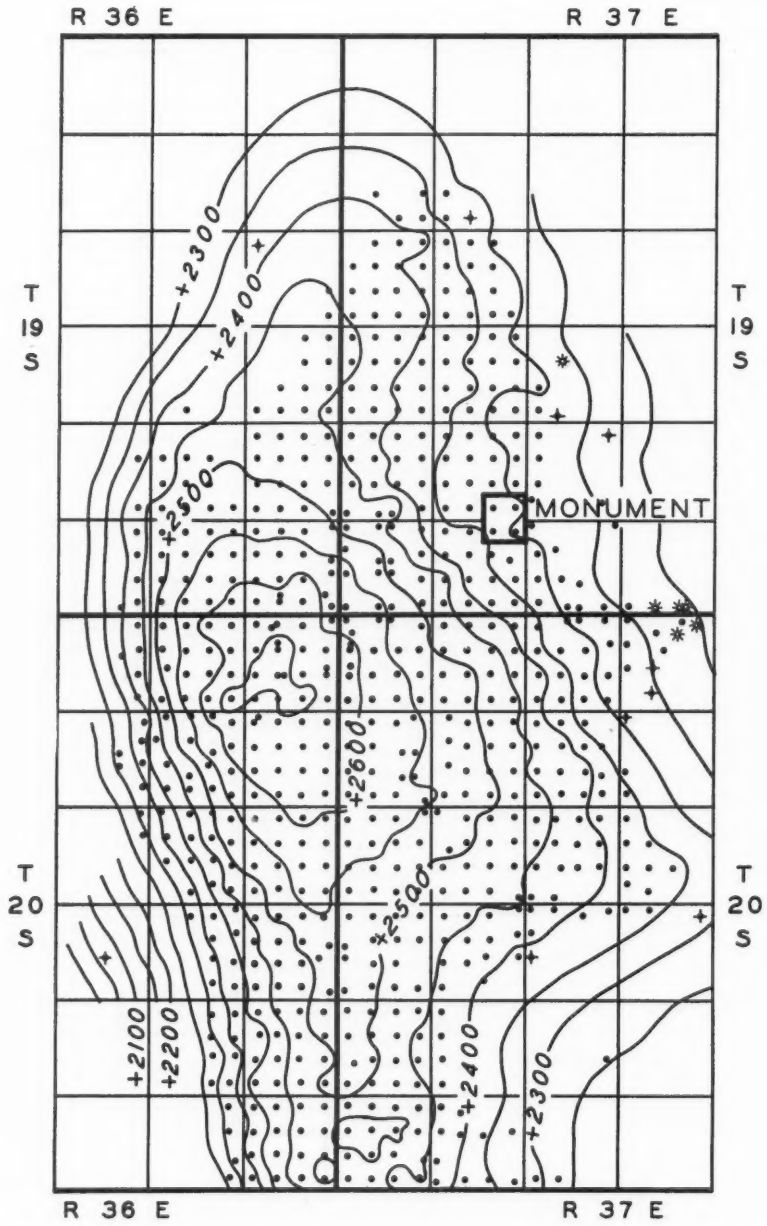

FIG. 14. Structure map of Monument area contoured on Rustler anhydrite from well data, 1942. Contour interval 50 feet.

Summarizing the results of the 1932–1935 correlation refraction work, it is found that:

(a) Correlation refraction shooting was as accurate as complete refraction profiling in locating upper Permian structures.

(b) Rapid reconnaissance could be obtained for an average of eight profiles per day were shot in comparison with the average of one to two complete refraction profiles.

The success of correlation refraction work in confirming Monument and locating Seminole persuaded Amerada to try this method on the Edwards Plateau in the latter part of 1936. The program resulted in locating the Todd and Barnhart structures. The method is still in general use in the Edwards Plateau Area.

PART THREE—1934–1950 REFLECTIONS

The third part of this paper describes the period from 1934 to 1950. Early reflection experimental work, economic factors that accounted for the slow introduction of the reflection technique, and the rapid expansion of the method after 1934 will be discussed.

Prior to 1934 there had been scattered efforts to obtain reflections in the West Texas Permian Basin. The first attempt occurred in 1929 at Shafter Lake, Andrews County, Texas, by a Geophysical Research Corporation crew. Good reflections were being obtained in other areas if the shot holes were dug to the water table. When it was found possible to dig to water in the dry lake bed with hand augers, an experimental profile was tried. A reflection was expected from the contact between the red bed and Rustler Anhydrite for well logs showed it to be a sharply defined lithologic change. The recording truck was located 1,000 feet away from the shot point and four detector stations spaced 200 feet apart were occupied. When the record was developed a whole series of reflections were present instead of one. Equally good results were obtained from several more profiles shot in the dry lake bed. Another dry lake was tried and again reflections were obtained. The experiments proved that reflections were obtainable if a way could be found to dig shot holes to the water table. Since the party had exhausted the supply of dry lakes and deep holes were still in the future, the party went back to refraction work.

By 1930 machine dug shot holes had become common practice and reflections were identified on refraction profiles in Ector County, Texas. The short recording positions on zero to 4,000 feet set-ups showed a distinctive arrival which checked the depth of the San Andreas lime when computed as a reflection. The results were shown to the local representative of the contracting oil company, and the pros and cons of reflection and refraction shooting were reviewed. Although reflection shooting was favored because of its greater accuracy, it was decided to continue the refraction program called for by the existing contract. So reflection work was shelved for the time being.

Also in 1930, an Amerada experimental crew stationed at Lovington had as

one of its problems—"To try reflection shooting." The area selected for the reflection experiments had caliche on the surface and although machine dug shot holes were used, the results were discouraging. Then, the dry lake experiments were repeated with good results. It was concluded from these experiments that caliche on the surface at the detector stations produced an interference pattern which obscured reflection energy on the record.

During the general increase of seismic activity in late 1934, reflection shooting was tried on a larger scale in southeastern New Mexico. Reflection crews spot correlated from shot point to shot point on a shallow reflection which was identified as coming from the Yates sand. Apparently the first attempt at continuous profiling was done by a Geophysical Service Incorporated crew in late 1934. The party shot a line from the west side of the Hobbs field to the National Securities #1 Linam well five miles to the west with shot points spaced one quarter of one mile apart. It is assumed that the results were unsatisfactory for the party moved away after shooting one line.

Seismic activity gradually decreased from a maximum of six crews to an average of three crews per month in 1935 and the period from 1936 to 1944 was very quiet. Continuous profiling was adopted as regular practice in 1936 and was used exclusively after 1937. The units that did operate in southeastern New Mexico up to 1944 had short assignments to evaluate acreage or to check small areas where other geophysical instruments had indicated an anomaly. An exception to this type of program was the broad reconnaissance program of the Shell Oil Company conducted in 1938 and 1939 in northern Lea and southern Roosevelt Counties.

The lack of interest in using seismic methods in New Mexico during 1936–1944 can be attributed to several factors. The use of the refraction method was limited because it required broad aereal coverage to evaluate a prospect, because it required large crews with high operating costs, and because it had a low resolving power. The reflection crews could not locate upper Permian structures because shallow reflections were too poor for spot correlation, or too erratic if continuous profiling was employed. From a *cost* standpoint the seismic methods were not on a competitive basis with other geophysical instruments, so the torsion balance, and later the gravity meter, the magnetometer, and electrical crews were preferred.

The increase in seismic activity that occurred in late 1944 can be attributed to the work of an Amerada crew. This crew moved to Lovington in July to check a subsurface San Andreas high in northwestern Gaines County, Texas. Increased structural relief was found with depth so the company decided to drill a deep test which resulted in the discovery of the Jones Ranch field in November, 1945. The extension of Devonian production from the Fullerton field to the Jones Ranch field, a distance of some thirty miles, materially changed geological thinking about the area which is now known as the northwest Shelf area of the West

Texas Permian Basin. Prior to 1945, shallow Permian production was sought. After 1945, the area was explored for pre-Permian structures.

Seismic activity increased until by the end of 1946, ten crews were operating in the Northwest Shelf area. An outstanding reflection was obtained in the area north and west of Tatum, New Mexico, and it was used for structural mapping. The original velocity assumption placed its depth near the top of the Pennsylvanian. Later it was identified from velocity surveys as the Abo, a lower Permian formation. Although lower Permian structure was being mapped on the Abo and Pre-Permian structures were being sought, the tempo of activity continued to increase during 1947 and 1948 and eighteen crews were operating by early 1949. In rapid succession, the Cross Roads, Knowles, Bagley, and Hightower fields were discovered. Each new discovery accelerated the use of the reflection seismograph and by September, 1950, thirty-four crews were operating in the Northwest Shelf area.

It may be inferred that most of the recent discoveries were found because the deep seated structures influenced the Abo appreciably. However, some pre-Permian structures such as Cross Roads do not materially influence the Abo, and the Abo reflection cannot be consistently mapped south of Tatum, New Mexico. Since many producing structures may still be found in Pennsylvanian and older formations, there continue to be attempts to explore below the Permian beds. Phantom horizons have been tried but lack of continuity makes structural interpretation uncertain. A few anomalies are being found with phantoms which appear to be worth testing by the drill.

In closing thanks are due to the Amerada Petroleum Corporation and to Dr. B. B. Weatherby for permission to use the maps and records presented with this paper, and to W. A. Carruth who prepared the figures.

AN ELECTROMECHANICAL TRANSDUCER SYSTEM FOR THE TRANSIENT TESTING OF SEISMOGRAPHS*

PIERRE M. HONNELL†

ABSTRACT

The transient response of seismographs is probably the more important instrumental characteristic of these devices and may be computed analytically subject to some simplifications. Recourse to direct laboratory tests would be a useful procedure for determining this type of response, both as a check on the theory and for the development applications.

Many early devices designed to test seismographs dynamically were rather crude affairs and aptly named "shaking tables." However, the prior art discloses with apparently but a single exception no shaking table truly capable of reproducing transient motions other than the natural oscillations of the device itself.

The purpose of this paper is to describe the theory and construction of an electromechanical transducer system which does reproduce vertical mechanical motions in the image of arbitrarily specified waveforms for the transient testing of seismographs. Results of such tests on commercial seismometers is included.

HISTORICAL PERSPECTIVE

Machines for the simulation of earthquake motions were devised in Japan in the 1890's: Milne and Omori (1892); Sekiya *et al.* (1894); Mano (1898 and 1900). These devices, utilized primarily for studying the reactions of man-made structures to strong motions, were aptly named "shaking tables." A natural development was the application of shaking tables to the scientific study of seismographic apparatus. Among the first to construct shaking tables for this specific purpose were Golitsyn (1902, 1912, 1914) and Mainka (1909). A variety of similar devices have been designed and constructed since that time, as is evident from the references cited in the Bibliography. With few exceptions, shaking tables described in the literature have primarily been of the type producing sustained sinusoidal motions. An excellent shaking table of this type, for example, was described by Lee and Irland (1932).

From the outset it has been recognized that the response of seismographs to transient motions is of fundamental importance. This response may of course be computed analytically but requires long and tedious calculations, especially if design data are required. Furthermore, the analysis can be based only upon idealized instruments. Finally, however, recourse to actual laboratory test is necessary to substantiate the computed transient response for any given seismograph.

The usefulness of apparatus for such tests was recognized very early, as is clear from Mainka's and Golitsyn's original work, much of which was concerned

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with transient phenomena. However, although mention is often made of transient motions obtainable with shaking tables, these transients turn out upon inspection to be primarily the few natural vibration modes of the table itself. They are definitely not arbitrarily assignable motions in the image of specified mathematical functions. One outstanding exception is the shaking table designed by Ruge (1936, 1943), for illustrations show that the platform of his device could follow earthquake records although it was a relatively slow-speed device.

The purpose of this paper is to describe the theory and construction of an electronically controlled electromechanical transducer system which does reproduce vertical mechanical motions in the image of arbitrarily specified waveforms, and which is applicable to the transient testing of seismometers of the types used in seismic prospecting techniques.

In the following sections, the physical apparatus is first described so as to furnish the framework to which the matrix analysis of the system may be affixed. This leads to a brief account of the transient analysis of the system, which is followed by a description and oscillograms showing the operation of the transducer with arbitrary waveshapes. As an example of the application of the transducer system, the transient responses of several commercial seismometers is included.

DESCRIPTION OF THE TRANSDUCER SYSTEM

It should be clearly understood at the outset that the electromechanical transducer and associated apparatus as actually constructed do not represent optimum designs, for the system was built principally as a laboratory device for test of the analysis. Nevertheless, experience gained from this model serves as a point of departure for improved physical designs.

The over-all system comprises an electromechanical transducer proper, shown in Figure 1, together with associated electronic amplifiers and signal generators. Figure 2 is a phantom view of the transducer, while Figure 3 and Figure 4 are sectional views, the latter giving dimensions in centimeters. The removable superstructure shown in the photograph (Figure 1) is not included in the other illustrations to simplify the views. This superstructure is very useful: for example, static displacements of the moving platform may be measured by clamping a dial indicator to the cross-bar, as shown in the Figure.

The short and stubby design of the electromechanical transducer was evolved after some experience with a shaking table following Lee and Irland (1932). This work indicated that long supporting members resonate to such an extent that the platform velocity is a highly erratic function of frequency for vibrations of more than 10 hertz (cycles per second), a wholly undesirable situation.

The 15.5 by 21.5 centimeter moving platform of the transducer is supported on double cantilever springs which constrain it to substantially vertical motions, with maximum displacements of ± 1.5 millimeters. The platform is driven mechanically by a hollow drive shaft to which are fastened the force coils of an upper

and a lower electromagnetic transducer. These force coils are energized by an electronic amplifier and are immersed in magnetic fields of about 0.2 webers per square meter flux density. The stationary field coils require 75 watts direct current power each for the production of the air gap magnetic fields. Some additional details of the mechanical construction and physical parameter magnitudes of the transducer may be found described by Honnell (1950).

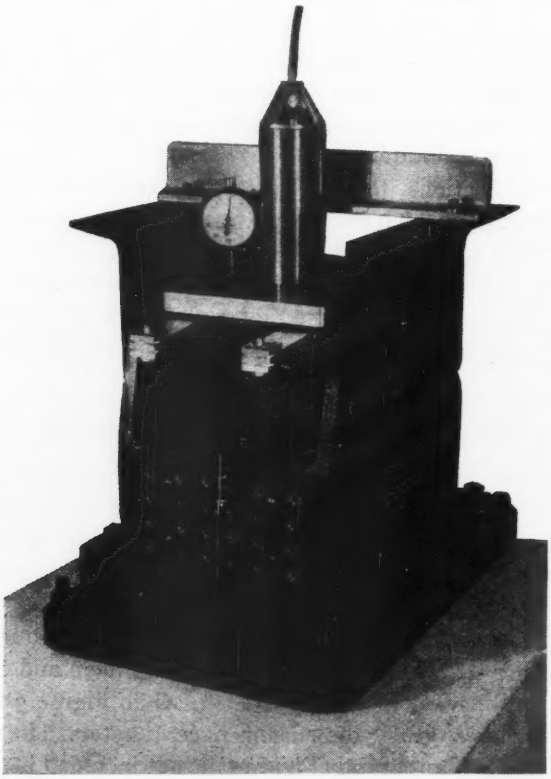

FIG. 1. Photograph of the Main Electromechanical Transducer, Showing Seismometer on Test. Dial Indicator is Useful for Static Displacement Calibrations.

Not only must the mechanical structure of the transducer be short and rigid, as previously mentioned, but the chassis of the device must be fastened to a firm support of considerable mass; otherwise, spurious modes of vibration will be coupled into the moving system. Although this coupled-circuit effect is objectionable, it may be allowed for in the calibration of seismometers with steady-state sinusoidal motions, since this is a step-by-step procedure. For motions comprising a plurality of discrete frequency components simultaneously such as in recurrent square waves, or arbitrary transients requiring continuous bands of frequencies, this is not possible. Even for steady-state testing, the coupled circuit effect, while not insurmountable, is inconvenient and undesirable.

Since bed-rock was not accessible, a practicable substitute was found in a floating concrete pier, as shown in Figure 5, to which the transducer chassis is firmly bolted. The mass of the concrete pier is estimated to be 0.5 metric ton and the sand base upon which it rests at 0.15 metric ton. The sand assists in isolating the pier from ambient mechanical vibrations. The void within the concrete was required merely to keep the floor loading within safe limits. The principal resonance of the mounting lies below 0.5 hertz, and is apparently a result of the

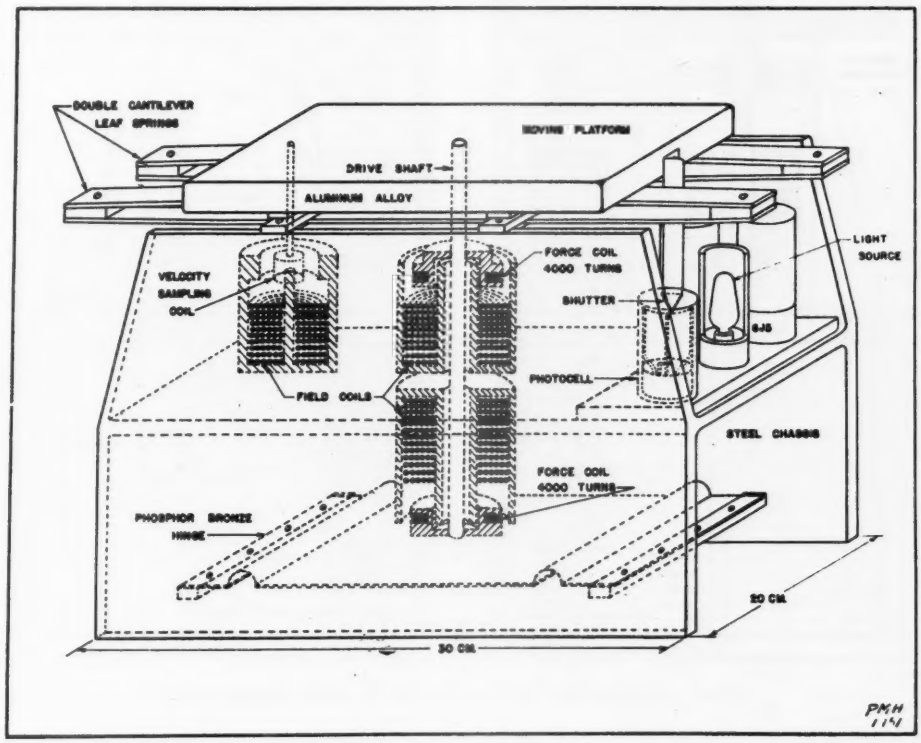

FIG. 2. Phantom View of the Main Transducer.

elasticity of the floor beams. The arrangement has been found to be quite satisfactory for the stringent requirements of transient studies, and has thereby made feasible the operation of the transducer system in a second-story laboratory.

The electronic components of the transducer system shown in Figure 6 include a three-stage amplifier chain with two independent feedback circuits. One feedback circuit derives a voltage proportional to the relative *displacement* of the platform, and is obtained by a photoelectric cell and light-shutter arrangement as shown in the illustrations. The second feedback circuit derives a voltage proportional to the relative platform *velocity*, and is obtained from a velocity sampling coil immersed in a constant magnetic field.

The remaining components of the system are the control signal voltage gener-

ators of recurrent and transient waveforms, which actuate the entire electro-mechanical system. Signal voltages of sinusoidal waveform are obtained from commercial oscillators. Very useful square waves are derived from the sine-wave oscillators by simple limiter circuits.

Arbitrary transient waveforms are generated by a photo-electric shadow-

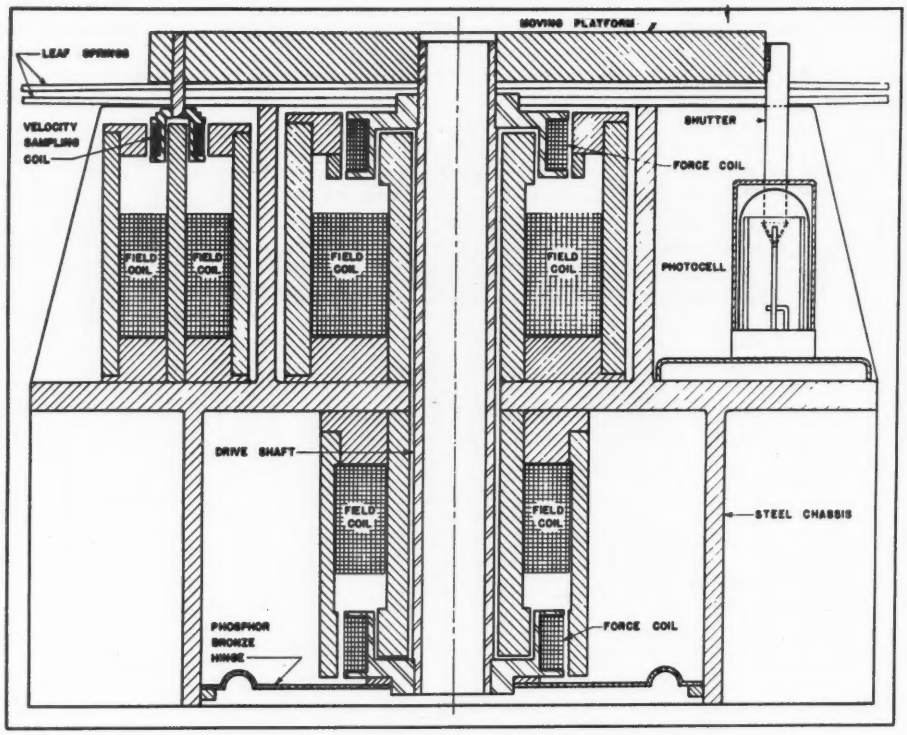

FIG. 3. Longitudinal Section Through the Main Transducer.

graph technique. Opaque masks cut to the desired waveforms intercept the light flux impinging upon a photoelectric cell. The output of the photo cell, after amplification, provides an electric voltage in the image of the desired waveform and this actuates the force coils of the main transducer. The mechanical arrangement of the arbitrary transient wave generator and the associated amplifier network are shown in Figure 7.

SYSTEM TRANSFER FUNCTION

The purpose of this section is to derive the system transfer function—that is, the analytical relationship between the electric signal input and the resulting mechanical motion of the moving platform. The transfer function is of fundamental importance since it not only provides the solution to the steady-state sinusoidal response of the system, but is also required in the application of the

Fourier and Laplace Transforms of the solution of transient motions.

The point of departure for the analysis is the symbolic network diagram of the electromechanical system. To this end, the actual connection diagram of Figure 6 is redrawn in a simplified schematic form, as shown in Figure 8. The latter diagram has been slightly generalized by placing the transient (or other) signal generator input on the grid circuit of the electron tube T_1 instead of its cathode.

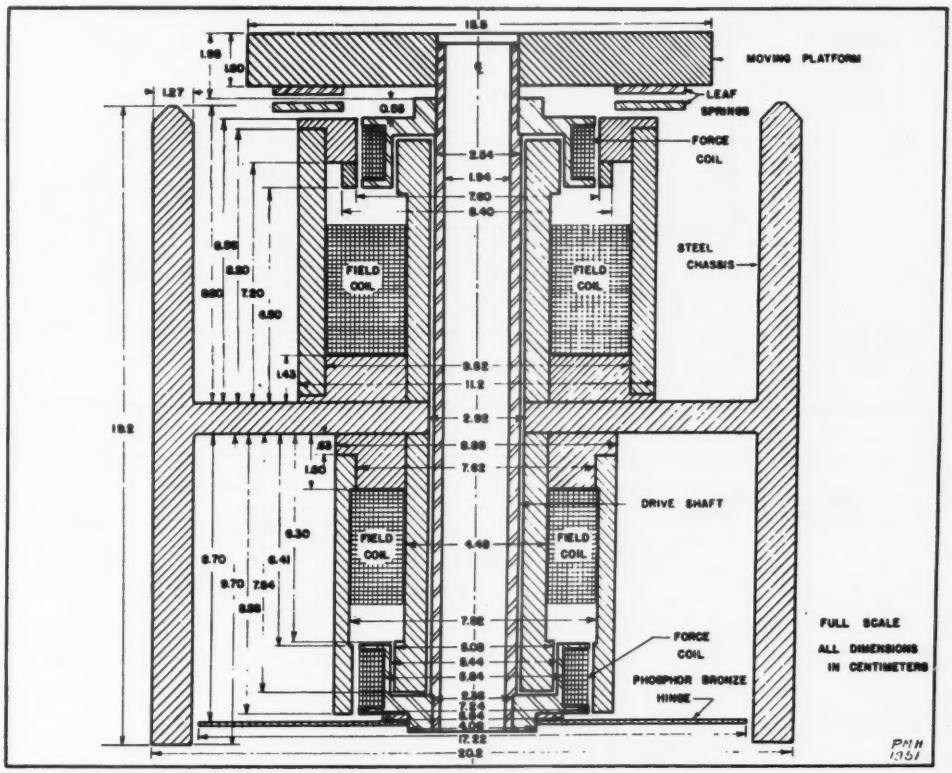

FIG. 4. Cross Section Through the Main Transducer with Dimensions.

This makes no significant change in the theoretical operation of the circuit.

The electromechanical network shown in Figure 8 may be considered as a principal transmission channel from the electric signal generator, connected to the grid of the tube T_1, through the power amplifier T_2, and thence transduced to the mechanical network. The output of the transducer is the mechanical motion of the transducer platform; that is, the displacement x_2 (and its time derivatives) acting against the external mechanical forces f_2. The actual net mechanical motion is also transduced to electrical signals and fed back to the input tube T_1 by the two subsidiary feedback paths through the tubes T_3 and T_4.

Since the feedback paths are coupled through electron tubes, they may be

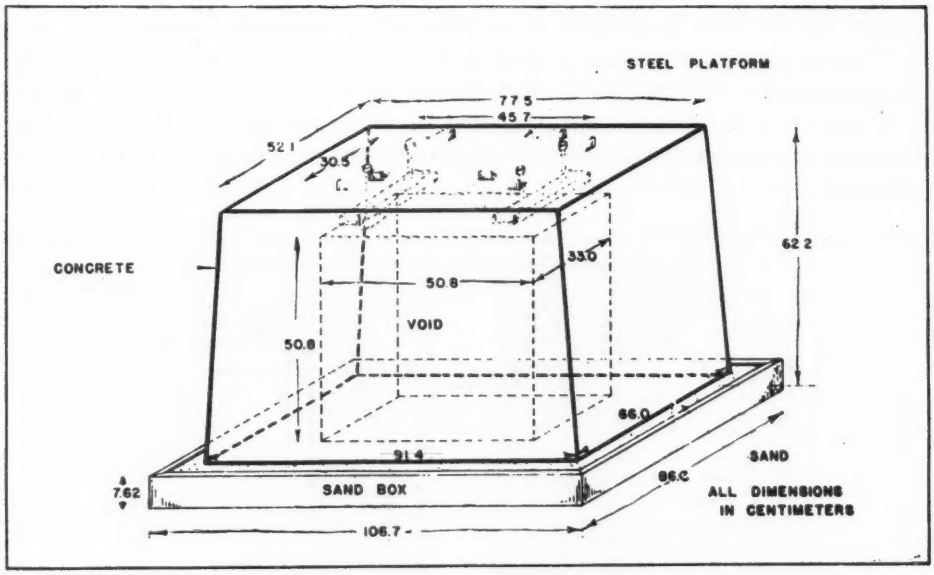

FIG. 5. Floating Pier Details.

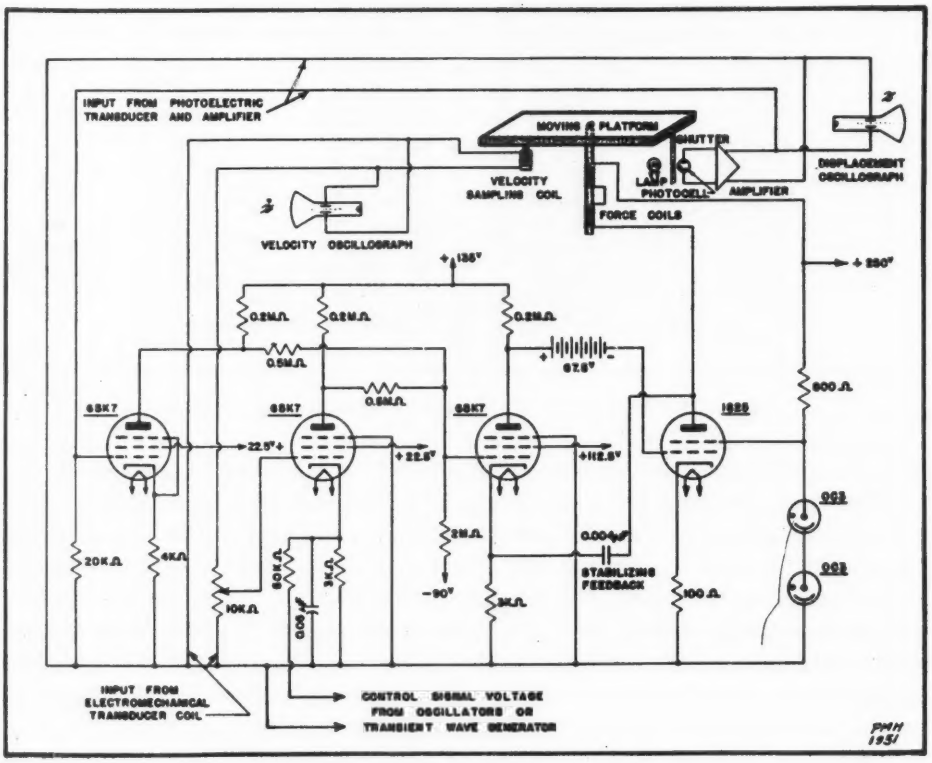

FIG. 6. Electronic Circuits of the Transducer System.

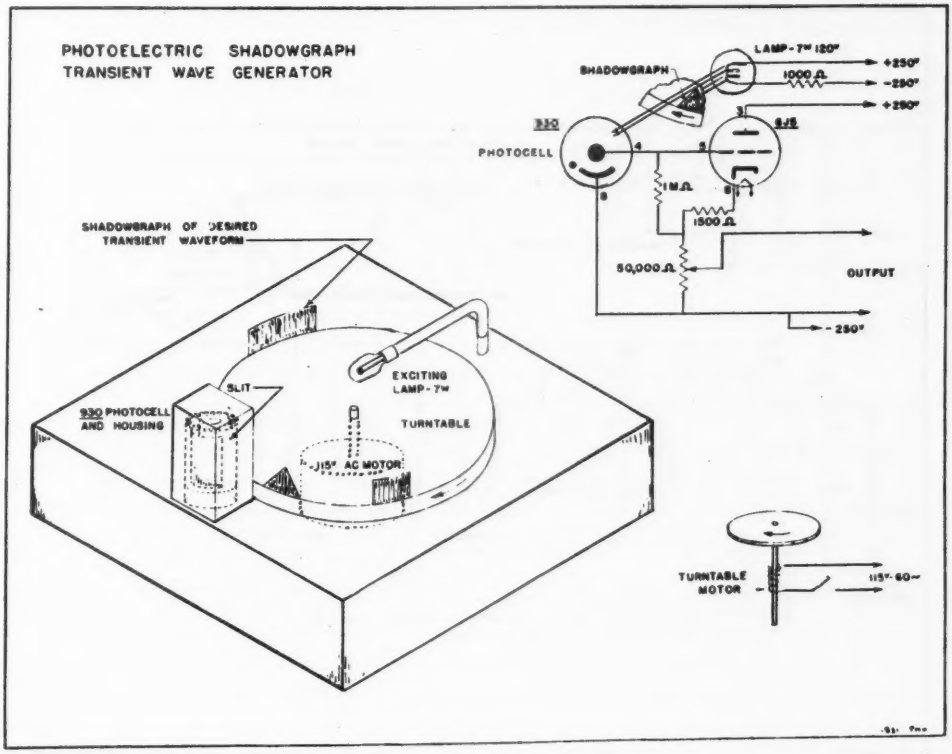

FIG. 7. Arbitrary Transient Wave Generator.

opened temporarily and analysis of the main transmission channel considered first; the feedback circuits are then closed and their contributions to the network operation determined so as to yield the complete transfer function.

The fixed parameter elements in the network, assumed as adjustable constants, are defined below and may be identified in Figure 8.

Electromechanical Network Parameters

- m the total suspended mass of the transducer moving platform, force coils, etc.
- M the mass added to the system by the seismometer on test clamped to the moving platform
- d the total residual dampance of the main transducer due to the motion of conducting metal in stray magnetic fields; air dampance, and the like (of small magnitude)
- s the equivalent stiffness of the springs suspending the moving platform
- BL_1 the transformance of the electromagnetic transducer Number 1, comprising both force coils; equal to the product of the constant air-gap flux density and the length of the force coil windings immersed therein

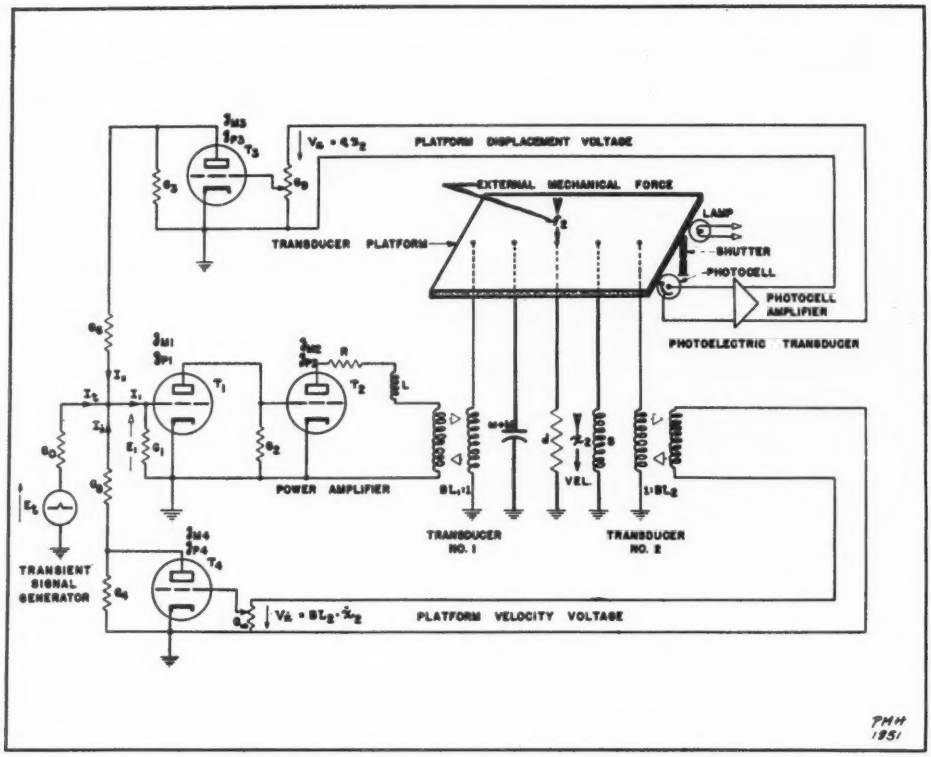

FIG. 8. Symbolic Network of the Electromechanical System.

R the total resistance of the force coils of the transducer Number 1

L the total inductance of the force coils of the transducer Number 1

g_{m2} the transconductance of the power amplifier electron tube T_2

g_{p2} the plate conductance of the power amplifier electron tube T_2

g_{m1}, g_{m3}, g_{m4} the transconductances of the voltage amplifier electron tubes T_1, T_3 and T_4 respectively

g_{p1}, g_{p3}, g_{p4} the plate conductances of the voltage amplifier electron tubes T_1, T_3 and T_4 respectively

G_1 the external grid-cathode coupling admittance of electron tube T_1

G_2 the coupling admittance between the voltage and power amplifier electron tubes T_1 and T_2

G_0, G_3 G_4, G_6, G_8, G_9, G_{10} electric network coupling admittances

BL_2 the transformance of the electromagnetic transducer Number 2, the velocity sampling device; equal to the product of the constant air-gap flux density and the length of the sampling coil winding immersed therein

a the coefficient relating the output voltage of the photoelectric transducer and the platform displacement

k_a the fractional setting of the voltage divider G_9

k_b the fractional setting of the voltage divider G_{10}

The electric and mechanical *variables* may similarly be found in Figure 8, and are defined below.

Electromechanical Network Variables

- λ the generalized angular frequency, herein taken as $\lambda=j\omega=j_t\pi F$ in which F is the frequency in hertz, or cycles per second
- f_2 the externally applied rectilinear, alternating, root-mean-square mechanical force on the transcuder platform.
- $\dot{x}_2$ the rectilinear, alternating, root-mean-square platform velocity
- E_1 the root-mean-square alternating voltage input to the voltage amplifier electron tube T_1
- I_1 the root-mean-square alternating current input to the voltage amplifier electron tube T_1 grid coupling admittance G_1
- E_t the voltage output from the transient wave generator
- V_x the output voltage from the photoelectric transducer (proportional to the moving platform displacement)
- $V_{\dot{x}}$ the output voltage from the electromagnetic transducer Number 2 (proportional to the platform velocity)
- I_t the equivalent current output from the transient wave generator
- I_x the equivalent current output from the photoelectric transducer electron tube amplifier T_3
- $I_{\dot{x}}$ the equivalent current output from the transducer Number 2 electron tube amplifier T_4

The analytical expression relating the electric input variables E_1 and I_1, and the mechanical output variables $\dot{x}_2$ and f_2 of the principal transmission channel may be written as a matrix product. With the feedback paths opened, this leads to the following equation (1),

$$\begin{bmatrix} E_1 \\ I_1 \end{bmatrix} = [T_1]\cdot[T_2]\cdot[Z]\cdot[BL_1]\cdot[\Upsilon]\cdot\begin{bmatrix} \dot{x}_2 \\ -f_2 \end{bmatrix} \tag{1}$$

in which the individual square matrices are associated with the physical subnetworks of the transmission channel. These matrices are defined in the following manner:

Electron Tube Amplifier T_1

$$[T_1] = \begin{bmatrix} -g_{p1}/g_{m1} & -1/g_{m1} \\ -g_{p1}G_1/g_{m1} & -G_1/g_{m1} \end{bmatrix} \tag{2}$$

Electron Tube Amplifier T_2

$$[T_2] = \begin{bmatrix} -g_{p2}/g_{m2} & -1/g_{m2} \\ -g_{p2}G_2/g_{m2} & -G_2/g_{m2} \end{bmatrix}. \tag{3}$$

Transducer No. 1 Electric Parameters

$$[Z] = \begin{bmatrix} 1 & R+\lambda L \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix}. \tag{4}$$

Transducer No. 1 Transformance

$$[BL_1] = \begin{bmatrix} BL_1 & 0 \\ 0 & 1/BL_1 \end{bmatrix}. \tag{5}$$

Transducer Mechanical Parameters (Including Mass M of Seismometer on Test)

$$[\Upsilon] = \begin{bmatrix} 1 & 0 \\ \lambda(m+M) + d + s/\lambda + (BL_2)^2 G_{10} & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \nu & 1 \end{bmatrix}. \tag{6}$$

Substituting equations (2) through (6) into (1) yields

$$\begin{bmatrix} E_1 \\ I_1 \end{bmatrix} = \frac{g_{p1} + G_2}{g_{m1} g_{m2} BL_1} \begin{bmatrix} (BL_1 \cdot BL_1 + \nu Z) g_{p2} + \nu & 1 + Z g_{p2} \\ (BL_1 \cdot BL_1 + \nu Z) g_2 G_1 + \nu G_1 & G_1 + G_1 Z g_{p2} \end{bmatrix} \cdot \begin{bmatrix} \dot{x}_2 \\ -f_2 \end{bmatrix} \tag{7}$$

in which Z and ν are defined by (4) and (6) respectively. This is the relation between the electric input and the mechanical output of the principal transmission channel, exclusive of the feedback contributions.

The consequence of feedback is inherent in the net voltage E_1 on the grid of tube T_1, and may be shown to be a linear function of three voltages: E_t from the transient or sinusoidal signal generator; the (displacement) voltage V_x from the photoelectric transducer; and finally the (velocity) voltage $V_{\dot{x}}$ from the transducer Number 2. This function may be shown to read

$$E_1 = \frac{G_0 E_t + \dfrac{G_6 g_{m3} k_a a}{g_{p3} + G_3 + G_6} \cdot x_2 + \dfrac{G_8 g_{m4} k_b BL_2}{g_{p4} + G_4 + G_8} \cdot \dot{x}_2}{G_0 + G_1 + G_6 + G_8 - \dfrac{G_6 \cdot G_6}{g_{p3} + G_3 + G_6} - \dfrac{G_8 \cdot G_8}{g_{p4} + G_4 + G_8}} \tag{8}$$

in terms of the parameters shown in Figure 8.

This relation may be written for convenience as:

$$E_1 = k_1 E_t + k_2 a x_2 + k_3 BL_2 \dot{x}_2 \tag{9}$$

in which k_1, k_2 and k_3 are involved constants of proportionality and include the coefficients k_a and k_b, the voltage divider settings of the feedback amplifier tubes T_3 and T_4, as defined by (8).

Assuming the suspended mass of the seismometer on test is negligible in comparison with its base of mass M, and that the externally applied forces are only electric—that is, $f_2 = 0$—the transfer function is obtainable from equations (7) and (9). After some manipulations and with the following additional abbreviations,

$$H_1 = \frac{g_{m1} g_{m2} BL_1 k_1}{g_{p1} + G_2} \tag{10}$$

$$K_0 = s + sRg_{p2} - \frac{g_{m1}g_{m2}BL_1k_2a}{g_{p1} + G_2} \tag{11}$$

$$K_1 = d + (BL_1)^2g_{p2} + (BL_2)^2G_{10} + (dR + sL)g_{p2} + R(BL_2)^2G_{10}g_{p2} - \frac{g_{m1}g_{m2}BL_1BL_2k_3}{g_1 + G_2} \tag{12}$$

$$K_2 = m + M + (m + M)Rg_{p2} + Ldg_{p2} + L(BL_2)^2G_{10}g_{p2} \tag{13}$$

$$K_3 = L(m + M)g_{p-}, \tag{14}$$

the system transfer function may be written in the following compact form:

$$\dot{x}_2 \equiv \lambda x_2 = \frac{H_1\lambda E_i}{K_0 + K_1\lambda + K_2\lambda^2 + K_3\lambda^3}. \tag{15}$$

TRANSDUCER SYSTEM RESPONSE TO ARBITRARY WAVESHAPES

With the system transfer function—equation (15)—derived, the response of the electromechanical transducer system may be computed by the Laplace Transform method for arbitrary signal voltages. For example, the transducer output velocity response $\dot{x}_2(t)$ to a unit step input voltage may be of the form

$$\dot{x}_2(t) = a_1e^{-\alpha t} + b_1e^{-\beta t} + c_1e^{-\gamma t}, \quad (t > 0) \tag{16}$$

and similarly the output displacement response $x_2(t)$ to a unit step input voltage may likewise be written as

$$x_2(t) = a_2e^{-\alpha t} + b_2e^{-\beta t} + c_2e^{-\gamma t} + d_2, \quad (t > 0) \tag{17}$$

for certain values of the coefficients of the transfer function.

It is true that the coefficients in equations (16) or (17), giving a type output response to a well-known input function, are simply related to the coefficients of the transfer function equation (15). However, it must be recalled that the coefficients H_1, K_0, K_1, K_2 and K_3 in the latter equation are themselves rather involved expressions in terms of the fixed and adjustable network parameters, equations (10)–(14) respectively. Furthermore, the coefficients k_1, k_2 and k_3 which appear in equations (10)–(14) are also themselves complicated functions of the electronic circuit parameters, as they are defined by matching coefficients between equations (8) and (9). It is clear, therefore, that the computation of the exact response of the transducer system for specific transient signal waveforms in general terms appears to be rather unremunerative for design purposes. If the system parameter magnitudes are known (or assumed) numerically, then these remarks do not apply so forcefully.

For design purposes, it is useful to consider idealized systems: this really means simplified versions of equation (15). Now in purely passive networks, the system transfer function can be altered only by changing the actual physical parameter magnitudes: that is, the resistances, inductances, stiffnesses, masses,

flux densities, and the like. The response of such a system can therefore be changed only with some difficulty, and then usually in discrete steps.

The electromechanical transducer system with its two independent feed-back paths is not so circumscribed. That is, the coefficients K_0 and K_1 of equation (15) are functions of the feedback connections, and can be varied smoothly at will over quite wide limits. The coefficients K_0 and K_1 can theoretically be made positive, zero or negative merely by changing the fractional settings k_a and k_b of the voltage dividers G_9 and G_{10}, Figure 8, and the polarities of the feedback transducer output voltages, or algebraic signs, of "a" and "BL_2". This permits the system response to be changed smoothly with great facility, without need for changing the actual physical network parameter magnitudes.

For example, it is clear that if K_0 can be made the dominant coefficient in the denominator of equation (15), then the transducer system *displacement* x_2 will be an image of the applied electric signal waveform E_t. That is, equation (15) reduces to

$$x_2 \doteq (H_1/K_0)E_t. \tag{16}$$

Similarly, if K_1 is made the dominant coefficient, then the transducer system *velocity* $\dot{x}_2$ will be an image of the applied electric waveform E_t, or

$$\dot{x}_2 \doteq (H_1/K_1)E_t. \tag{17}$$

That the idealized conditions expressed by equations (16) and (17) may actually be approximated to a marked degree is demonstrated by the steady-state sinusoidal frequency-response of the system; and perhaps even more clearly by its arbitrary waveshape or time-response.

System Frequency-Response

The wide variety of steady-state sinusoidal frequency-responses obtainable from the transducer system physically constructed as previously described, is exhibited by Figures 9, 10, and 11.

For the purpose of orientation, the electromechanical system operation *without feedback* is shown in Figure 9; this is achieved by adjusting the voltage dividers G_9 and G_{10}, Figure 8, such that the coefficients k_a and k_b are zero. Figure 9 displays the relative peak magnitudes of the sinusoidal platform displacement x_2—and the corresponding velocity $\dot{x}_2$—for a constant amplitude alternating signal voltage E_t of frequency varying from 1 to 300 hertz. These system response curves clearly show the pronounced peaks at about 28 hertz due to resonance of the mechanical parameters.

By introducing both displacement and velocity feedback of the proper magnitude and polarity, the transducer system response shown in Figure 10 may be obtained. It should be noted that by this adjustment of the system parameters K_0 and K_1, the *displacement* response x_2 of the transducer system becomes substantially independent of frequency. This is indicated by the solid line (A) in

Figure 10, which is "flat" from zero to 20 hertz, dropping off sharply for higher frequencies. Moderate loading of the platform—see curve (B)—does not substantially change the response, but does require some resetting of the feedback controls. Since these adjustments lead to mechanical platform displacements in the image of the applied electric signal inputs, as indicated by equation (16),

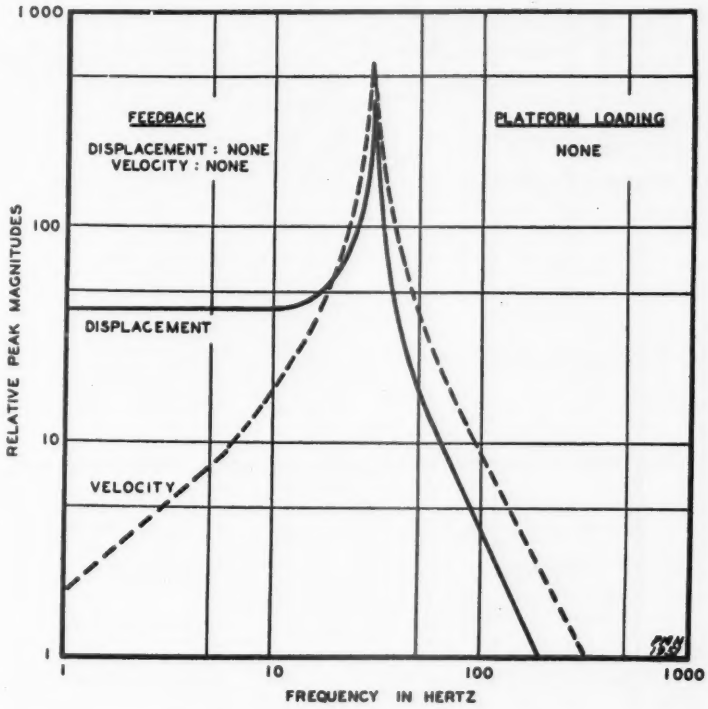

FIG. 9. Transducer System Steady State Sinusoidal Transfer Response Without Feedback.

this may be called the "displacement mode" of operation of the system, and represents a "low-pass" type of transfer function.

Introduction of the maximum possible velocity feedback of positive polarity yields the interesting results shown in Figure 11, due to the dominance of the coefficient K_1. Under these conditions, the platform *velocity* response $\dot{x}_2$ may be maintained substantially uniform over the frequency range from 8 to 150 hertz, as indicated by the dashed curve in Figure 11. This means that the transducer system sinusoidal velocity response is in the image of the applied electric signal voltage, as postulated by equation (17), over the specified frequency interval. These adjustments of the network coefficients lead to what may therefore be called the "velocity mode" of operation of the system, and is clearly a "band-pass" type of transfer function.

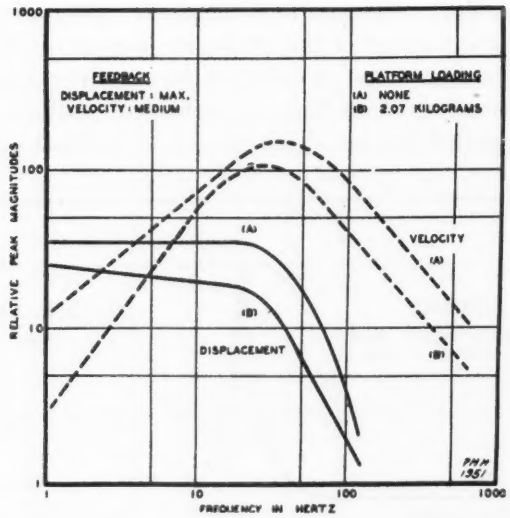

FIG. 10. Transducer System Steady-State Transfer Response in Displacement Mode.

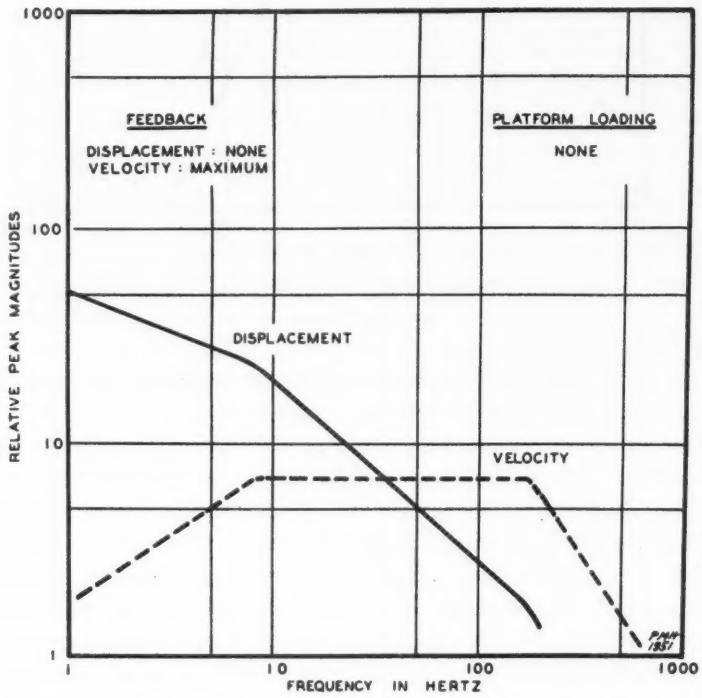

FIG. 11. Transducer System Steady-State Transfer Response in Velocity Mode.

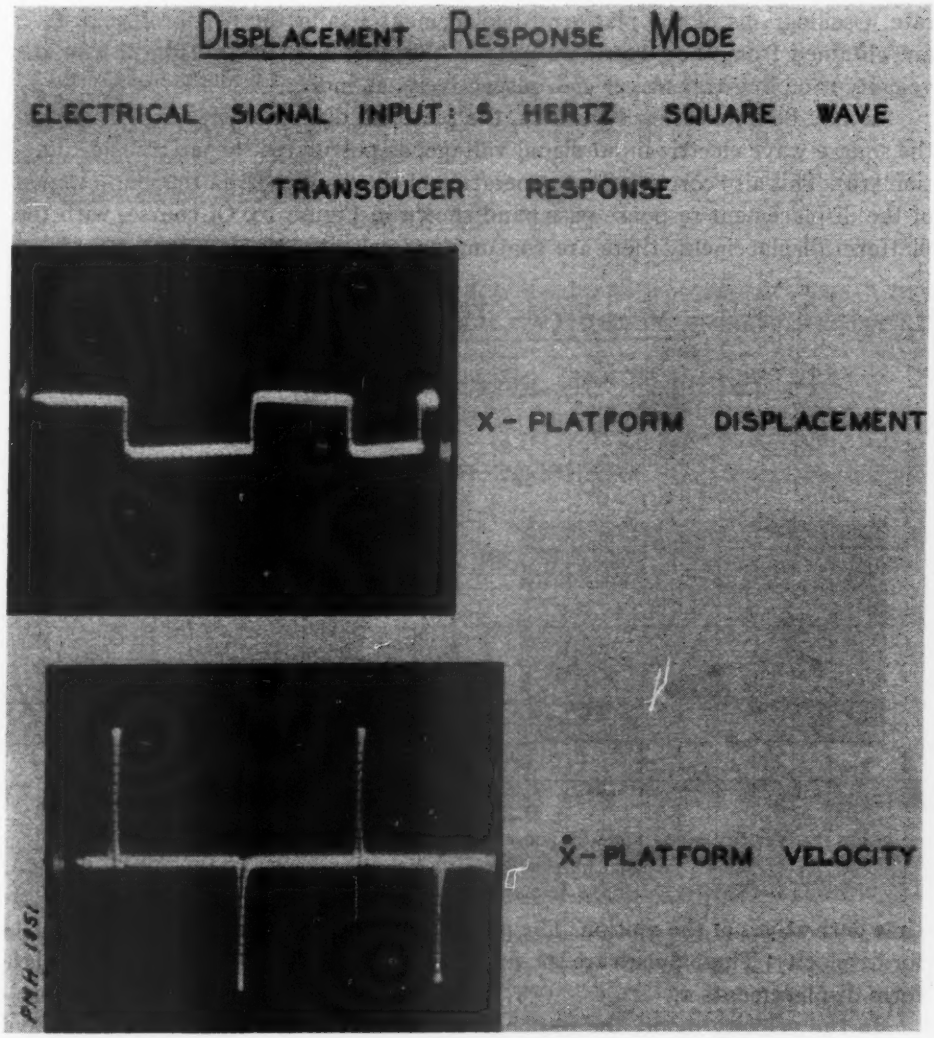

FIG. 12. Displacement Mode Time-Response of Transducer System to Square Wave Electric Signal Input at a 5 Hertz Repetition Rate.

System Time-Response

The variety of steady-state sinusoidal frequency-responses of the transducer system exhibited by Figures 9, 10, and 11 have their counterpart in the system time-response, that is, the ability of the transducer system to execute mechanical motions in the image of electrical signals.

A typical time-response of the transducer system in the "displacement mode" is depicted in Figure 12. This illustration shows the displacement and velocity response of the transducer to an electric square wave input of 5 hertz repetition

rate. Oscillograms of the platform displacement x, and the platform velocity $\dot{x}$ are obtained from the electric outputs of the photoelectric transducer and the velocity sampling transducer coil, respectively, as indicated in Figure 6.

As may be noted from Figure 12, the platform displacement x is a replica of the square-wave electric input signal voltage, as postulated by the transfer function (16). This also corresponds to operation of the transducer in the "flat" region of the displacement response pass-band shown in Figure 10. Of course, with the platform displacement, there are concomitant velocity, acceleration and higher

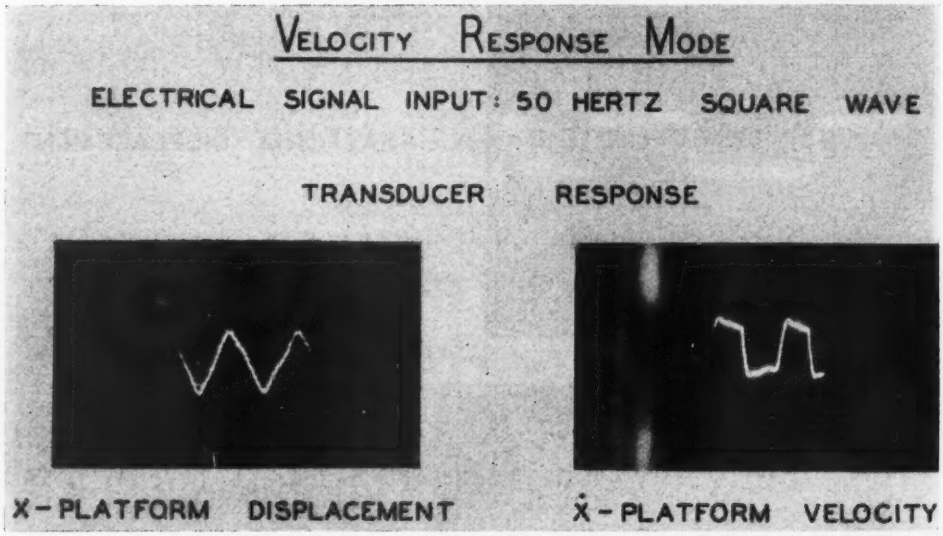
VELOCITY RESPONSE MODE
ELECTRICAL SIGNAL INPUT: 50 HERTZ SQUARE WAVE
TRANSDUCER RESPONSE
X - PLATFORM DISPLACEMENT
Ẋ - PLATFORM VELOCITY

FIG. 13. Velocity Mode Time-Response of Transducer System to Square Wave Electric Signal Input at 50 Hertz Repetition Rate.

time derivatives of the motion. The pulses shown in Figure 12 represent the platform velocity. These pulses are the first time derivatives of the square-wave platform displacements x.

In the velocity mode, the response of the transducer system to square wave electric signal input results in a square wave output of velocity as is postulated by equation (17). Figure 13 shows the platform velocity $\dot{x}$, and the corresponding displacement x, for a 50-hertz repetition rate square-wave electric signal input. The repetition rate must of course be chosen in the velocity pass-band of the transducer system; that is, in the approximate center of the "flat" portion of the velocity response curve shown in Figure 11. The concomitant platform displacement in this case is a saw-tooth wave, the integral of the displacement. It is clear that the fidelity of the velocity image is not as high as that of the displacement image. This is principally a result of the relatively more limited velocity pass-band width for the particular physical apparatus, as compared to the low-pass band width.

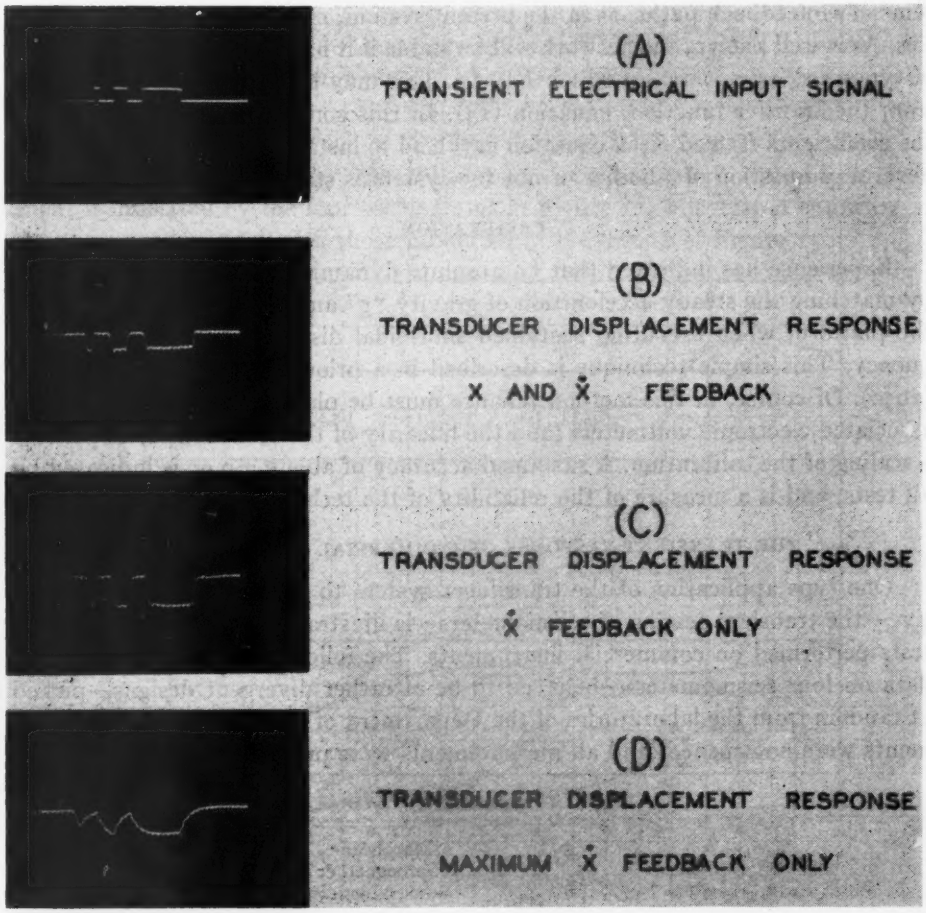

FIG. 14. Transducer System Response (B) in Displacement Mode, for Arbirtary Wave Shape Electric Signal Input (A). Effect of Loss of Displacement Feedback is Indicated in (C), While (D) Shows System Operation with Excess of Velocity Feedback.

The transducer system performance in the "displacement mode" for arbitrary non-recurring waves is demonstrated by Figure 14. The oscillogram (A) shows the electric signal input, and (B) the corresponding transducer platform displacement. It is interesting to note that the use of velocity feedback only—as indicated in (C)—does not yield the fidelity of the adjustment in (B). Furthermore, an excess of velocity feedback does not yield "velocity mode" operation, as is clear from the oscillogram (D).

STABILITY

No description of a feedback system is complete without a discussion of the stability question. Suffice it to recall that this is the big problem of feedback sys-

tems. Two feedback paths, as in the present system, merely magnify the difficulties. As is well known, the network will be stable if it has free modes of oscillation of types $x_0e^{\lambda t}$ or $x_0 \cdot t \cdot e^{\lambda t}$ for which $Re\lambda < 0$. This may be determined analytically from the transfer function, equation (15). In this connection, negative signs of the coefficients K_0 and K_1 in equation (15) lead to instability. Physically, there is never any question of whether or not the system is stable!

CALIBRATION

Experience has indicated that an absolute dynamic calibration can be made by matching the steady acceleration of gravity "g" and the peak acceleration of the platform when executing sustained sinusoidal displacements of known frequency. This simple technique is described in a prior publication, see Honnell (1950). Of course, in this method reliance must be placed upon the accuracy of associated electronic voltmeters (and the linearity of the transducers) to provide a scaling of the calibration. A sustained accuracy of about ± 0.95 is indicated by all tests, and is a measure of the reliability of the technique.

THE TRANSIENT RESPONSE OF COMMERCIAL SEISMOMETERS

One type application of the transducer system to its principal design objective—the transient testing of seismometers—is illustrated by the results of such tests performed on commercial instruments. The following table lists pertinent data on four seismometers—believed to be of rather divergent designs—picked at random from the laboratories of the Department of Geophysics. These instruments were not opened, and all measurements were purely external.

COMMERCIAL SEISMOMETERS

	Century Geophysical Corporation	Macelwane (Sprengnether Instrument Co.)	The Texas Company	Western Geophysical Company
Model	301	—	—	—
Serial Number	C3759AZ	3	T-462	3006
Overall Mass, Kilograms	2.15	6.9	3.45	2.6
Undamped Frequency f_0, hertz	6.5	13.25	50	45
Output Circuit Resistance, ohms, dc	134	7,000	13,500	109
Inductance, henrys, at 1,000 hertz	20.7×10^{-3}	0.5	50	8.9×10^{-3}
Inductance, henrys, at 100 hertz	23.0×10^{-3}	2.0	20	0.45

For purposes of orientation, the steady-state frequency-response and undamped natural frequency of each seismometer was first determined on the transducer. These are the usual data obtained on "shaking tables." The frequency-response curves for the four seismometers are presented in Figure 15. This figure shows the root-mean-square output voltage across the electrical shunting resistances tabulated in the legend, per meter-per-second velocity of the seismometer case. The calibrations are, therefore, absolute. The measured undamped frequencies f_0 are also indicated in Figure 15.

The time-response of the Century seismometer to square waves of displacement is shown in Figure 16. The upper oscillograph trace in each instance is the Century seismometer voltage output; the lower trace is the actual seismometer case displacement.

The time-response of each of the four different seismometers to a *single* 200 microns peak amplitude by 180 millisecond duration square-wave of displacement is indicated by the four oscillograms in Figure 17. The output shunting resistances are identical with those tabulated in the legend of Figure 15.

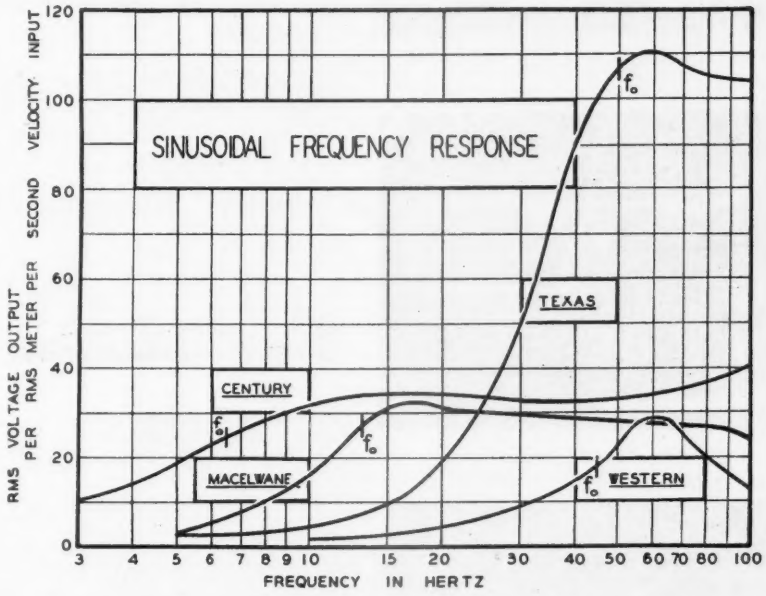

FIG. 15. Steady-State Frequency-Response of Commercial Seismometers. Century Geophysical Corporation—Unshunted. Macelwane (Sprengnether Instrument Company)—Shunted 1,000 ohms. The Texas Company—Unshunted. Western Geophysical Company—Shunted 100 ohms.

The last illustration, Figure 18, shows the time-response of the same four seismometers to a single 100 micron peak by 25 millisecond duration pulse of displacement.

The explicit information on the transient response of the seismometers on test indicated by Figure 16, 17, and 18 certainly requires no comment. It should clearly be noted, however, that the transducer was executing transient motions substantially in the image of the electric signal input although loaded with as much as 15 pounds!

RÉSUMÉ OF RESEARCH AND OBJECTIVES OF FUTURE DEVELOPMENTS

The transient testing transducer system as described does not include all the refinements which experience indicates should be incorporated. This follows from the fact that the transducer was designed principally as a laboratory model for

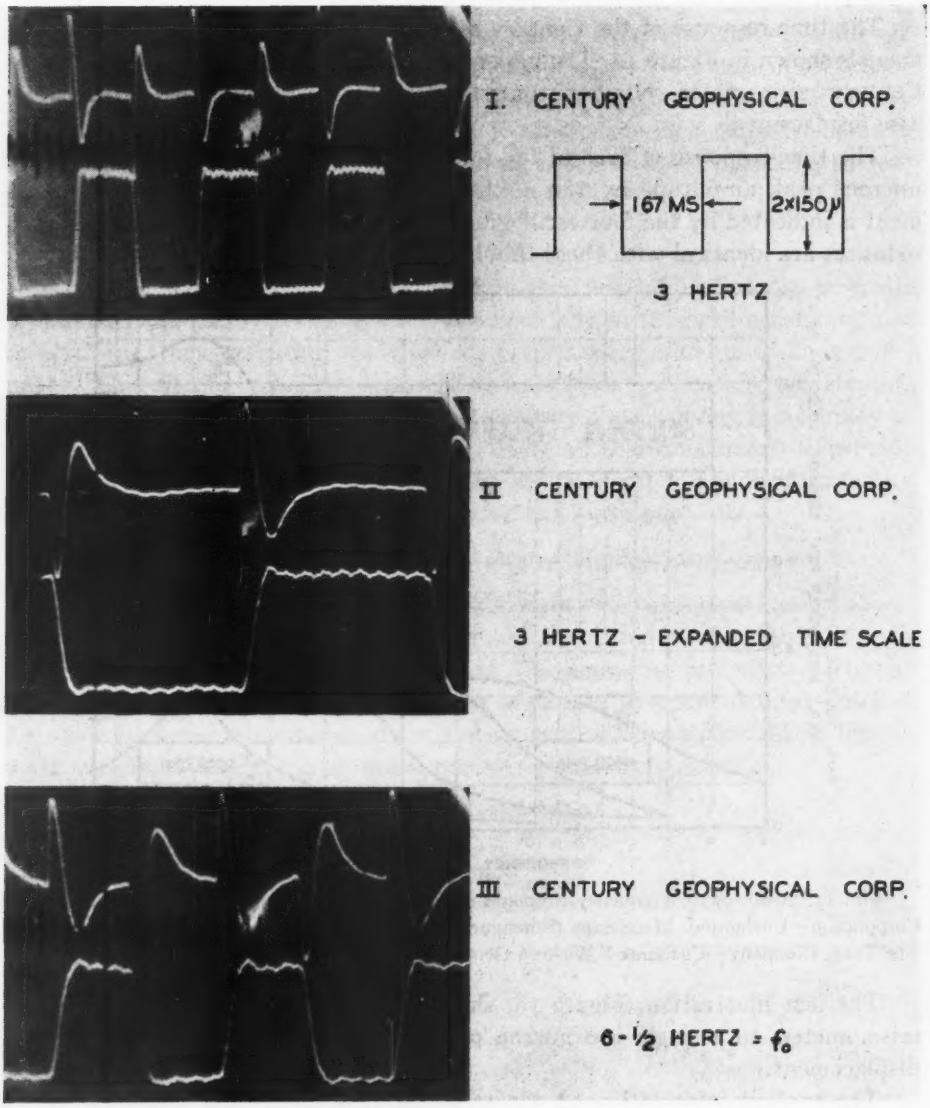

FIG. 16. Time-Response of Century Geophysical Corporation. Model 301 Seismometer. Input —Square Waves of Displacement. Output—Electric Voltage on Open Circuit.

verifying the system analysis. Nevertheless, the device is exceedingly useful even in its present form. In that connection, the results of the transient tests on the commercial seismometers described in the last section speak for themselves. It is clear that the character of the transient response of electromechanical systems is not easily predicted from their steady-state frequency response.

The extraordinary value of the transient testing transducer system as a tool

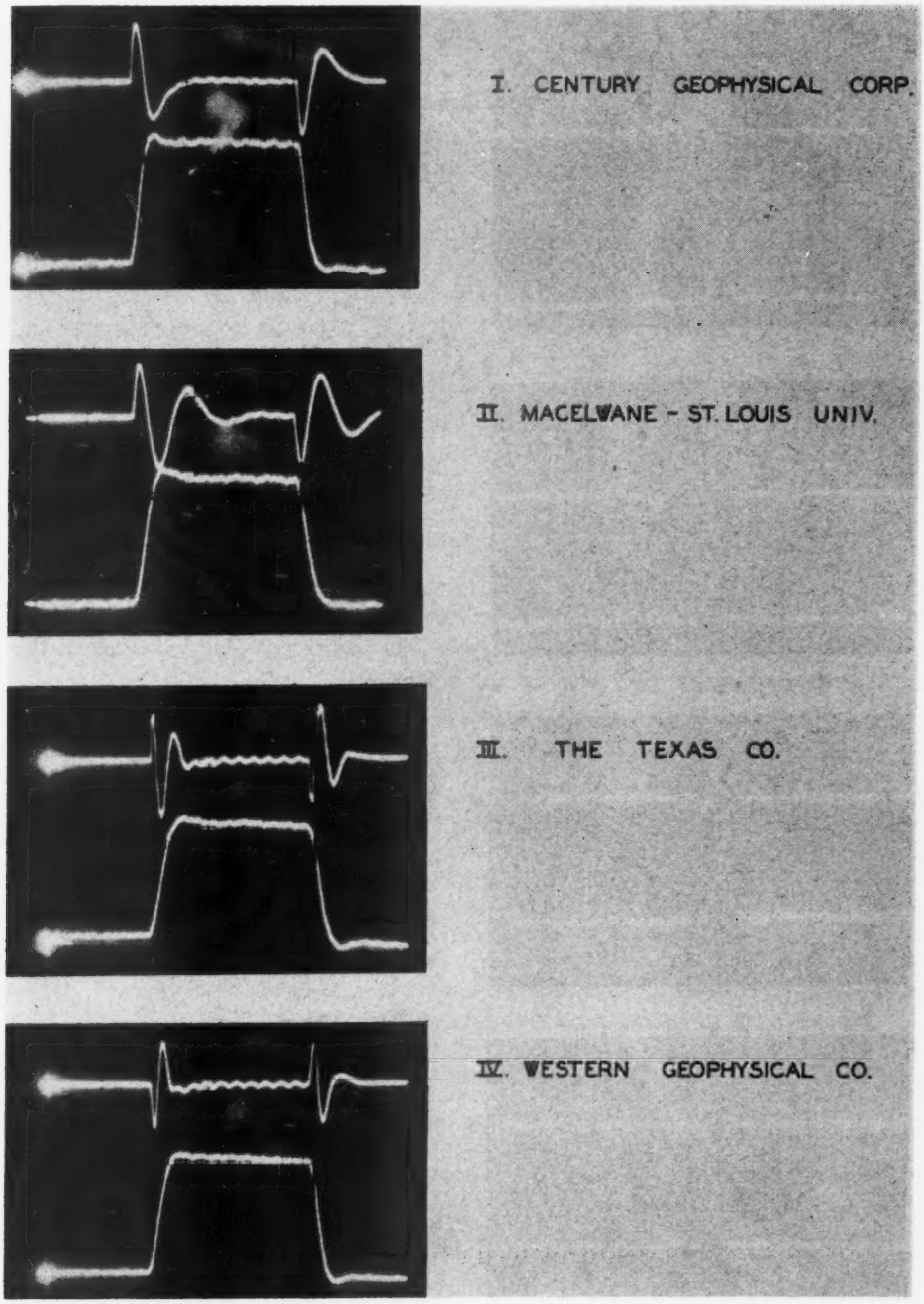

FIG. 17. Time-Response of Commercial Seismometers to a Single 200 Micron Peak by 180 Millisecond Duration Square Wave of Displacement. I—Century Geophysical Corporation—Unshunted. II—Macelwane (Sprengnether Instrument Company)—Shunted 1,000 ohms. III—The Texas Company—Unshunted. IV—Western Geophysical Company—Shunted 100 ohms.

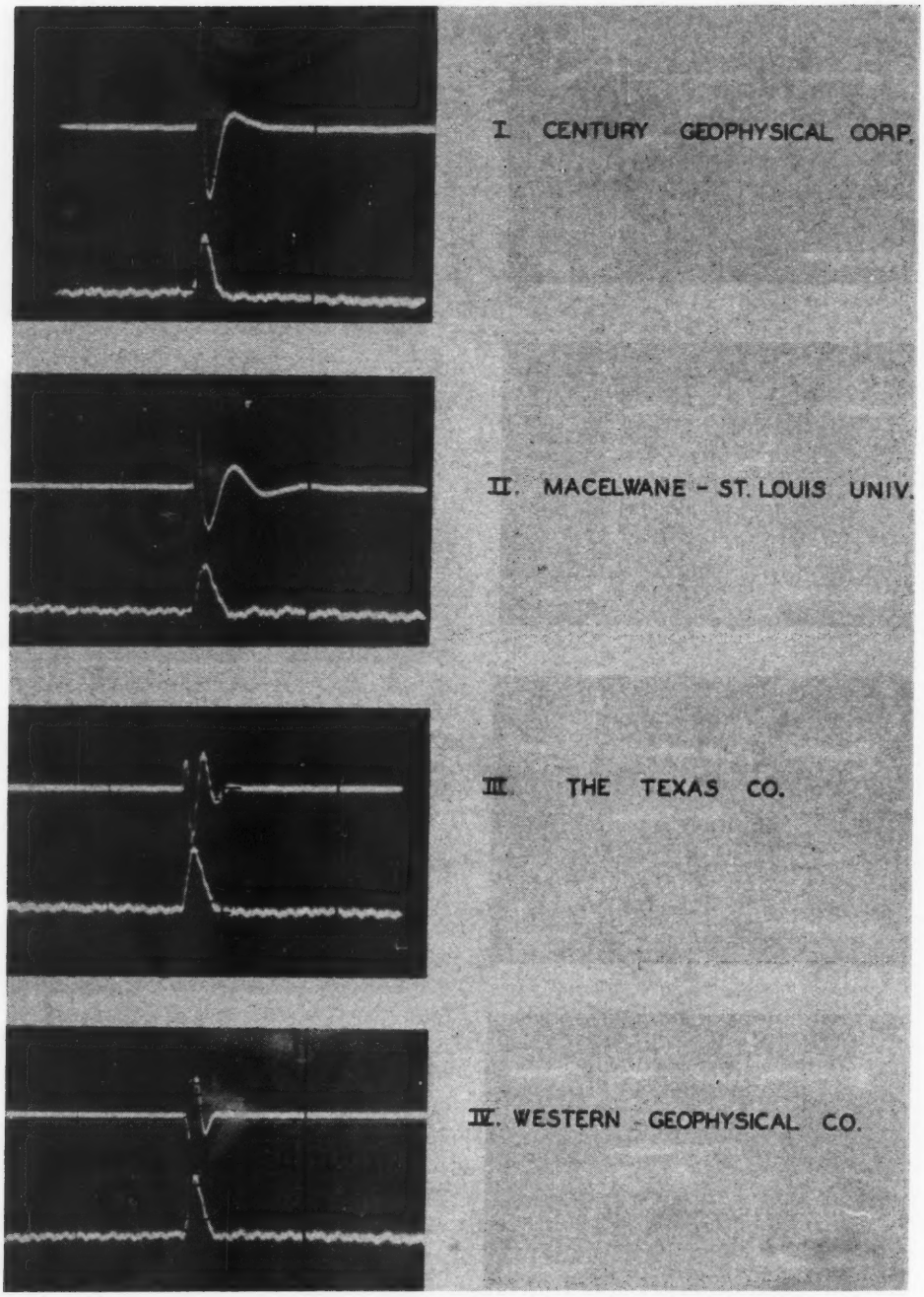

FIG. 18. Time-Response of Commercial Seismometers to Single 100 Micron Peak by 25 Millisecond Duration Pulse of Displacement. I—Century Geophysical Corporation—Unshunted. II—Macelwane (Sprengnether Instrument Company)—Shunted 1,000 ohms. III—The Texas Company—Unshunted. IV—Western Geophysical Company—Shunted 100 ohms.

in research on electromechanical—or purely mechanical—systems can therefore be taken as established.

As objectives of future developments of the transducer system proper, in contrast to its applications as a research tool, there comes immediately to the forefront the need for increasing the range of amplitudes of motion and the fidelity of response in the displacement and velocity modes of operation. This is theoretically easy to do, merely requiring higher-powered electron-tube amplifiers, more gain in the feedback channels, and a higher natural period for the mechanical system itself. (In that connection, additional third and fourth feedback paths for acceleration $\ddot{x}$, and rate of change of acceleration, $\dddot{x}$, are indicated by the form of the transfer function.)

Unfortunately, practice is sometimes more difficult than theory. For additional feedback paths increase the possibilities of instabilities; and in any event *residual* electric and mechanical parameters set limits which are difficult to elude. The objectives of these future developments are, however, clear-cut.

ACKNOWLEDGMENT

This paper summarizes one phase of a research program on seismograph instrumentation pursued under the direction of the Reverend Dr. James B. Macelwane, S. J. in the Department of Geophysics of Saint Louis University. It is a pleasure to acknowledge the inspiration and counsel of Reverend Macelwane, and the searching review of the research in progress by Dr. Florence Robertson.

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Karl Dyk, "On the Reduction of Seismograms Obtained in Shaking-Table Experiments," *Bulletin Seismological Society of America*, Vol. 25, No. 2 (April, 1935), 119–137.

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Prince Boris Golitsyn, *Vorlesungen Über Seismometrie*. Leipzig und Berlin: B. G. Teubner (1914).

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Prince Boris Golitsyn, "Zur Theorie der Mechanischen Registrierung," *Imperial Academy of Sciences*, St. Petersburg (1912).

Quotation from paper "Meiner neuen Untersuchungsplattform, welche man beliebig, vorgeschriebene und bekannte harmonische Bewegungen ausfuhren lassen konnte, . . . " Does not give details of apparatus nor of results.

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Describes elementary table on wheels sufficiently large to mount small masonry walls and other engineering materials for tests on effects of motions simulating earthquakes.

Kiyoshi Kanai and Katsutada Sezawa, "Effect of Distribution of Masses in a RAHMEN FLOOR on Seismic Structural Vibration, and Model Experimental Confirmations of that Effect with a New Vibration Table," *Bulletin Earthquake Research Institute, Tokyo Imperial University*, Vol. XVIII, No. 21, Part 3 (September, 1940), 370–383.

Section 4, page 374, describes a new Vibration Table. Shows recent work using horizontal table on rollers with concrete base for apparatus. Table driven by 1 horsepower electric motor and eccentric, through spring coupling, which is found to be necessary to obtain sinusoidal motions.

Hirosi Kawasumi and Zyuniti Kinosita, "An Experimental Study of Initial Motion of Seismographs Caused by Motions of Short Duration," *Bulletin Earthquake Research Institute*, Tokyo Imperial University, Vol. XIV, No. 30, Part 3 (September, 1936), 339–353.

Paper describes horizontal motion shaking table driven by ½ horsepower electric motor through eccentric and shaft. Table motion damped by vanes in oil. This provided means for steady-state testing of seismographs. Response of seismograph to wavelet impulses also shown. These transient table vibrations were however produced by the unaided hands of the operator.

Dunford Kelly, "A reaction Type Shaking Table," *Geophysics*, IV, No. 1 (January 1939), 69–75.

Describes a steady-state vertical shaking table. A motor-driven unbalanced mass imparts force to mass of 500 pounds supported from three coiled springs.

Horst Kohler, "Ein Neuer Schütteltisch zur Eichung und Prüfung Hochempfindlicher Erschutterungsmesser," *Zeitschrift für Technische Physik*, Vol. 22, No. 9 (1941), 209–215.

Describes elementary type of electromagnetic transducer with circular disc membrane for table support, similar to a dynamic loudspeaker. Highly undamped device.

F. W. Lee, and G. A. Irland, "Construction of Master Mechanical Oscillator for Testing Seismic Recorders and Other Allied Apparatus," *Technical Paper 518, Bureau of Mines, United States Department of Commerce*, Washington (1932).

An excellent reference to the construction of an actual shaking table. Electromechanical drive of light table supported by spring and constrained to strictly vertical motion. Uses electronic and optical means for monitoring table motion.

Dr. C. Mainka, "Eine Neue Seismische Untersuchungsplatte," *Publication du Bureau Central de L'Association International de Séismologie*, Série A, *Mémoires*, Strassburg (1909).

In his own words, Mainka describes the transducer as: "Eine Platte hangt an drei Seilen an Einem passenden Gestell. Durch ein geeignet eingerichtetes Hebelsystem wird diese hängende Platte in die gewünschte Bewegung versetzt und diese durch ein passend angeordnetes zweites Hebelsystem registriert."

B. Mano, "Report on the Improved Form of the Shaking Table," *Shinsai Yobo Chosakai Hokoko (Reports of the Imperial Earthquake Investigation Committee in the Japanese Language)* Number 21, (July 28, 1898), p. 5.

One of the earliest descriptions of a shaking table, in the Japanese language, and is apparently an improvement over the device described by Sekiya (1894).

B. Mano, "Appareil pour l'Étude Théorique des Tremblements de Terre," *Imperial Earthquake Investigation Committee*, Publications of the Earthquake Investigation Committee in Foreign Languages, No. 3, Tokyo (1900), 85–86.

Describes the improved version of the shaking table, presumably the same as Mano (1898), but translated into French. Comprises wooden platform which could be given horizontal and vertical motions independently by ingenious mechanical linkages.

H. E. McComb and Frank Wenner, "Shaking Table Investigations of Teleseismic Seismometers," *Bulletin Seismological Society of America*, Vol. 26 (October 1936), 291–316.

An elementary form of seismograph platform for testing large apparatus, comprising a concrete (horizontal) platform suspended by three wires, driven by vibrating reeds or unbalanced flywheels.

J. Milne and F. Omori, *Seismological Journal of Japan*, Vol. I (1892).

Quoting from Omori (1900): "Describes experiments on the fracturing and overturning of columns by horizontally applied motions. Work carried on in 1891 in the work-shop of the Engineering College of Tokyo Imperial University." This is apparently one of the earliest references to work with shaking tables or platforms.

Frank Neumann, "The Accuracy of Seismogram Analysis as Revealed by Shaking Table Tests," *Publication du Bureau Central Séismologique International*, Série A, Fascicule 16 (1946), 56–66.

Use of shaking table described by Ruge (1936) in determination of seismograph accuracy.

L. H. Nishkian, "Vertical Vibration Recorders for the Golden Gate Bridge," *Bulletin of the Seismological Society of America*, Vol. 37, No. 2 (April 1947), 81–88.

Shows pictures and briefly describes vertical motion platform which is said to provide a maximum displacement of 90 inches, and periods from 2.9 seconds to 9½ seconds. Driven by motor and gear assembly through a Scotch yoke. Largest displacement amplitude shaking table described in literature.

F. Omori, "Seismic Experiments on the Fracturing and Overturning of Columns," *Publications of the Earthquake Investigation Committee in Foreign Languages*, No. 4, Toyko (1900), 69–141.

Paper describes work on fracturing and overturning of columns performed on horizontal shaking table described by B. Mano (1900). This work is similar to previous researches on the same subject performed earlier by Milne and Omori (1892).

H. R. Prescott, "Seismic Receptors," *Geophysics*, VI, No. 3 (July 1941), 239–244.

Brief description of a shaking table. Electronic amplifier drive to moving table, and includes optical lever for monitoring motion.

A. Ramspeck, "Eine Schüttelplatte zur Untersuchung von Seismographen," *Zeitschrift für Geophysik*, Vol. 8 (1932), 71–74.

An horizontal table on rollers, motor driven, with some results of experiments.

G. Reutlinger, "Eine Experimentelle Ueberprufung der Theorie der Schwingungsmesser," *Gerland's Beitrage Zur Geophysik*, Vol. 24 (1929), 168–240.

Describes tests of vibrometers on vertical and horizontal shaking tables of simple design.

F. J. Rogers, "Experiments with a Shaking Table," *The California Earthquake of 18 April 1906 Report of the State Earthquake Investigating Commission*, Vol. I, Part II (1908), 326–335.

Study of destructiveness of artificial motions simulating earthquakes on foundations of structures using a wood platform on rollers driven by direct-current motor through eccentric.

Edmond Rothe and Alphonse Remy, "Appareil de Synthèse de Mouvements Périodiques," *Publication du Bureau Central Séismologique International*, Série A, *Travaux Scientifique* (1927), 98–118.

Clever mechanical arrangement for compounding several separate sinusoidal motions of different frequencies and amplitudes for driving table described by Mainka (1909).

Arthur C. Ruge, "Earthquake Effects on Elevated Water Tanks," *Civil Engineering*, Vol. 5, No. 8 (August 1935), 455–459

Shows elementary form of shaking table in Figure 7, page 458. Transients produced by suddenly releasing table from a pulled-back position. Photographic observation of table motion.

Arthur C. Ruge, "New Shaking Table Reproduces Earthquakes," *Civil Engineering*, Vol. 6, No. 3 (March 1936), 222.

Summary of a paper presented at ninety-seventh convention of the American Association for the Advancement of Science, St. Louis, December 31, 1936. Shows picture of new table, substantially as described in next reference.

Arthur C. Ruge, "A Machine for Reproducing Earthquake Motions Direct from a Shadowgraph

of the Earthquake," ***Bulletin of the Seismological Society of America***, Vol. 26, No. 3 (July 1936), 201–205.

Description of the horizontal shaking table built at Massachusetts Institute of Technology, hydraulically driven with photo-electric shadowgraph cam for input signal generation of special (non-harmonic) waveforms, including actual earthquake records. Fundamentally a servo-mechanism.

Arthur C. Ruge, "Earthquake Resistance of Elevated Water-Tanks," ***Transactions, American Society of Civil Engineers***, Vol. 103 (1938), 889–949.

Results of further tests on water-tank models with shaking table described by Ruge (1936). Paper also published in Proceedings of American Society of Civil Engineers (May 1937), 883.

Arthur C. Ruge and H. E. McComb, "Tests of Earthquake Accelerometers on a Shaking Table," ***Bulletin Seismological Society of America***, Vol. 33, No. 1 (January 1943), 2–12.

Description of apparatus tested and comparison of results, for irregular shaking table motions. Shaking table illustrated is apparently same as Ruge (1936).

S. Sekiya, S. Tanabe, B. Mano, A. Tanakadate, A. Inokuty, and F. Omori, "A Shaking Table for Seismic Experiments," ***Shinsai Yobo Chosakai Hokoko, (Reports of the Imperial Earthquake Investigation Committee in the Japanese Language)***, No. 2 (August 25, 1894).

Apparently one of the earliest descriptions of a shaking table.

A. Sieberg, "Neuere Untersuchungen der Reichsanstalt für Erdbebenforschung über bautechnische Erdbebensicherung," ***Zeitschrift für Geophysik***, Vol. XVII, Heft 3/4 (1941), 83–102.

Tests on model houses and structures with a "Stosstisch," stated as being similar to L. S. Jakobsen's (1929) "Schütteltisch." No other details. Shows 13 figures of photographical views of model structures collapsing.

Harold Washburn and Raymond Olesen, "Transient Testing of Seismic Recording Apparatus," ***Geophysics***, V, No. 4 (October 1940), 337–347.

Includes description of vertical motion shaking table (page 343). Comprises a large cubical mass supported by four groups of rubber bands, and driven by inertia force supplied from subsidiary electromechanically coupled driver in turn elastically suspended from the main table.

EXPLORATION WORK IN MEXICO*

ANTONIO GARCIA ROJAS†

ABSTRACT

Since 1940 Mexico has increased exploration work in search of new oil fields. Most of the exploration has been done in the Gulf Coast area where all existing Mexican oil fields are located. A brief résumé is given of the main problems of the different provinces under exploration and a list of the fields discovered by Petróleos Mexicanos in the different provinces of the country. Geophysical methods have been responsible for location of a very large percent of the new fields. To compare the intensity of exploration in the United States and Mexico, the amount of seismic and gravity-meter work and of wildcat drilling per million barrels of production is given for both countries.

The data shows that Mexico's level of geophysical exploration, per million barrels of oil produced, is very close to that of the United States. A very marked increase in the intensity of exploration is shown for both countries.

Wildcat drilling in Mexico has been less intensive than in the United States but shows a definite tendency to increase; its present level is very close to that of the United States during 1940. The writer is of the opinion that the difference in intensity of wildcat drilling shown in the data presented is actually smaller than appears as there is a certain amount of duplication in the United States because of leaseholding problems.

I. INTRODUCTION

During the last fifteen years there has been a very great increase in the oil production of Mexico, and therefore in order to maintain adequate reserves it has been imperative to expand exploration activities to a level which has no parallel in the history of the country.

The purpose of this paper is to give a brief outline of the exploration work done by Petróleos Mexicanos and to compare the amount of exploration work done in Mexico with that of the United States.

II. DESCRIPTION OF AREAS EXPLORED

General

Mexican oil production has come from oil fields located in the sedimentary basins of the coastal plain of the Gulf of Mexico, where production has been found in rocks varying in age from Miocene to Cretaceous. There are several other sedimentary basins where exploration has been carried on, but no production has been found.

Geological information available indicates that the most important future development in Mexico will take place in the Gulf Coastal plain, and most of the exploration work is being done in this area.

The gulf coastal plain of Mexico has been divided into four main provinces,

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and commercial production has been found in three of them. Going from north to south these provinces are:

a) North-east Mexico
b) Tampico-Tuxpan
c) Veracruz Embayment
d) Isthmus Tabasco

On the Pacific coast is found the big sedimentary embayment of Lower California which is regarded as the most promising area for oil development after the Gulf coastal plain. See Figure 1.

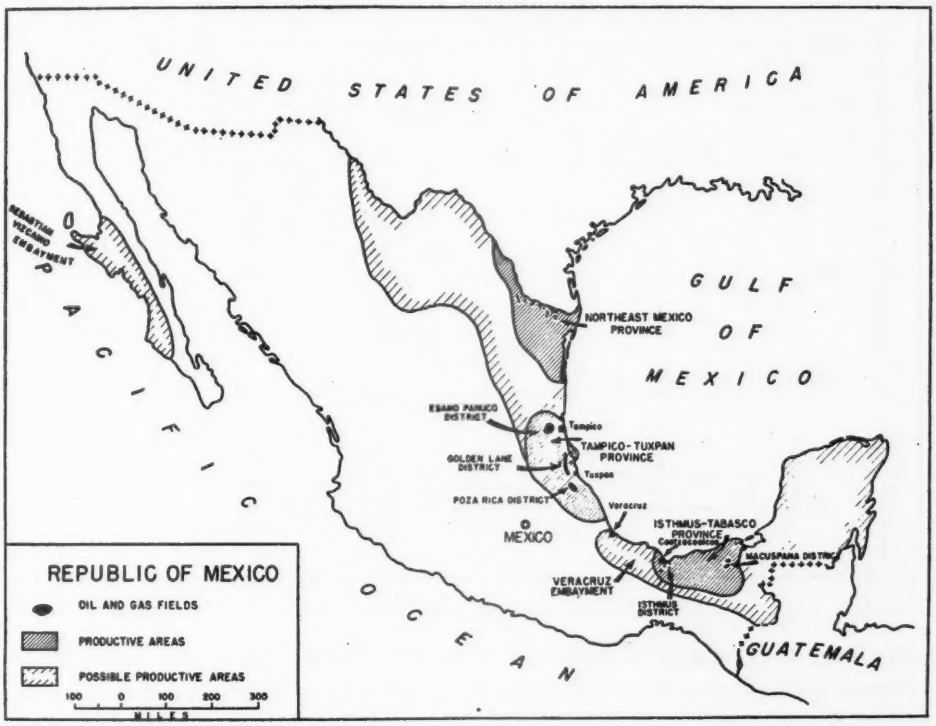

FIG. 1

Surface geological work of both regional and semi-detailed type has been done on all these embayments, and detailed work has been done on those areas where surface geology is capable of giving reliable subsurface information. However, very often the outcropping formations lie unconformably upon deeper sediments and local structures can not be determined by surface geological work. Furthermore, wildcat information is rather limited in many areas and most of the new development has been based on geophysical exploration.

Geophysical work has been done in Mexico since 1923, and although it was

the basis for discovery of Poza Rica and El Plan oil fields, which are the biggest in the Tampico and Isthmus districts, most of the work done until 1940 was concentrated in areas of small extension or was of reconnaisance type with widely separated lines. Therefore, when Pemex began operations, very little information was available on which to base exploration wells or detailed surveys. For that reason it was decided to cover the most promising areas with gravitymeter work having a density of observation capable of showing regional trends and of detect-

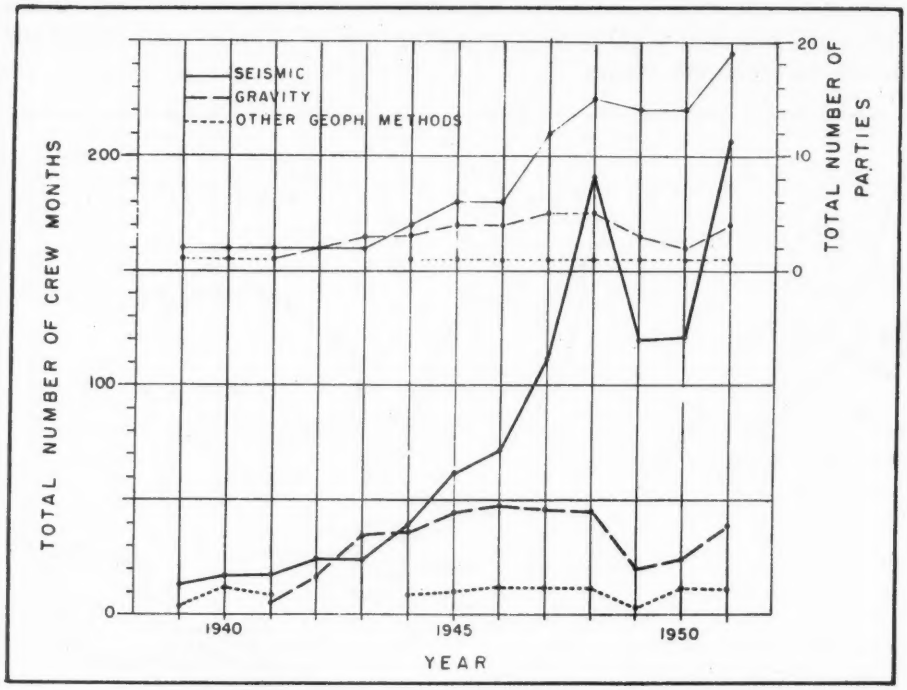

FIG. 2

ing individual anomalies of significant extension. For such purpose a network of polygons with sides of about 5 kilometers (3 miles) was observed using all roads and trails available.

As there was very little structural and stratigraphical information available, it was thought that a more detailed gravity network than this would not increase materially the value of the gravity map.

Seismic work was started in most areas after the gravity work had advanced to a point where long range programs could be planned.

At present, there are operating in Mexico 20 geological parties, 20 seismic parties, 4 gravity parties, and 1 electrical. There are also 27 rigs which are doing exploration drilling only.

The increase of geophysical exploration activities in Mexico is shown in Figure 2.

The general trend shows a continuous increase since 1943, and exploration will undoubtedly keep at a level similar to or bigger than that of 1951.

Exploration in North-east Mexico

Figure 3 shows the area known as the North-east Mexico province, which is limited at its northern boundary by Texas, on the south by the Soto la Marina river, and to the west by the Sierra Madre mountain front.

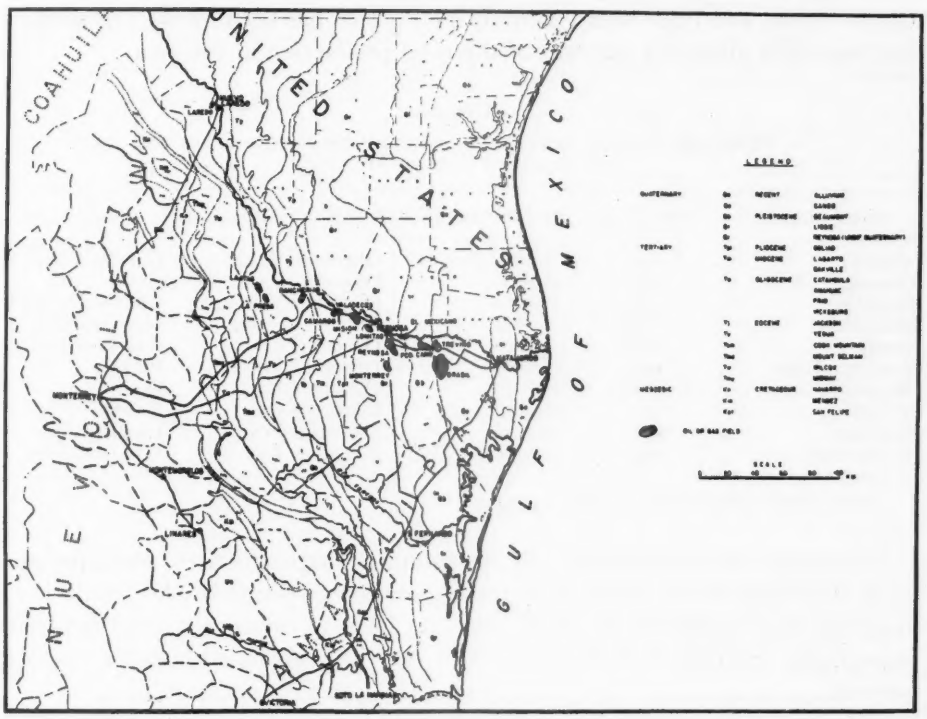

FIG. 3. Geological Map of Northwest Mexico.

In the early development of the province, 56 new field wildcats were drilled, based mainly on geological information. As a result of this work 4 gas fields were discovered (La Presa, Lajitas, Rancherías, and Laredo), all of which fall in the belt where Eocene rocks outcrop.

In 1943, when Petróleos Mexicanos started a continuous exploration campaign in the area, it was decided to use surface geology or gravity work as reconnaisance tools in order to select the most promising areas for seismic work for the purpose of locating new field wildcats. Subsurface geology locations were reserved for those cases in which enough detailed information was available.

As a result of this exploration program, during the 1943–1951 period, 9 oil or gas fields have been found, 8 of which were based on geophysical work.

Most of the exploration done in the 1943–1951 period, has been done in search of Oligocene production, but there are good prospects for Eocene production, especially in the area north of the Monterrey-Reynosa highway, and the Cretaceous rocks also offer a good prospective horizon.

The Tampico-Tuxpan province extends between the Soto la Marina and Nautla rivers, and is limited on the west by the Sierra Madre mountain front. Most of the oil produced in Mexico has come from limestones of middle Cretaceous age, from the three producing districts in this province (Ebano-Pánuco, Golden Lane, and Poza Rica). Tertiary production has been found, but so far it has been only about 0.1 per cent of the total production in the area.

TABLE 1

PRODUCTIVE FIELDS DISCOVERED BY PETROLEOS MEXICANOS IN THE NORTH EAST ZONE OF MEXICO

Name of Field	Disc. Year	Basis for Location	Productive Formation	Production
Mision	1945	Surface Geology	Oligocene Vicksburg	Gas-Distillate
Camargo	1947	Seismic	Oligocene Vicksburg	Gas
Reynosa	1948	Seismic	Oligocene Vicksburg	Gas-Oil-Distillate
Valadeces	1948	Seismic	Eocene Jackson	Gas-Distillate
Brasil	1948	Seismic	Oligocene Frio	Gas-Distillate
Fransisco Cano	1949	Seismic	Oligocene Frio	Oil-Gas
Monterrey	1950	Seismic	Oligocene Frio	Oil
Treviño	1951	Seismic	Oligocene Frio	Gas-Oil
Lomitas	1951	Seismic	Oligocene Frio	Gas-Distillate
El Mexicano	1952	Surface Geology	Oligocene Frio	Gas-Distillate

Note: Date completed as to April, 1952.

Limestone facies vary widely in the Tampico-Tuxpan district, which presents local challenges to the ingenuity of the exploration geophysicist. Accumulation is found in traps varying from narrow fracture zones to coral reefs, and the surface topography changes from flat country to very hilly areas, with slopes up to 25 percent.

The discovery of the Ebano-Pánuco and Golden Lane district was based mainly on surface seepages and the development of these fields was based on subsurface geology.

The Poza Rica oil field was found by a torsion balance survey and its development is being based on subsurface geology and seismic work.

As a result of the complicated facies distribution in the province, very little drilling was done before 1940 outside of the producing districts, and, therefore, the potentialities of a great part of the province are still to be evaluated. For this reason the search for new fields in the Tampico-Tuxpan province will undoubtedly be based on geophysical work, which will help to establish subsurface structural conditions and subsurface geology which will help to determine the type of accumulation to be expected under ordinary operating conditions. A large number of wildcat wells will have to be drilled on seismic structures in order to

make a good facies map which will then serve a basis for planning the development of different areas of this province.

Previous to 1938, some big areas of the Tampico-Tuxpan province had been covered by torsion balance surveys and Petróleos Mexicanos has filled in the gaps with a regional gravity survey made along roads and trails existing between the Pánuco and Nautla rivers in all parts of the area where surface conditions permit reliable gravity results. A belt near the coast about 60 kilometers wide

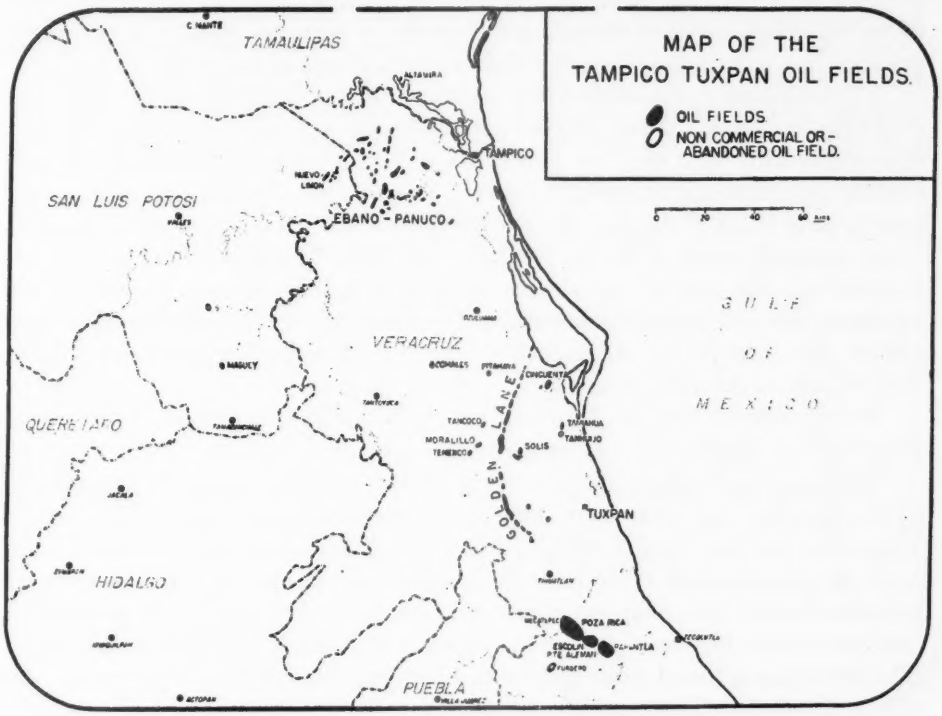

FIG. 4

between the Soto la Marina and the Pánuco rivers has been covered by gravity-meter work and a program to cover all the remaining prospective area in this province is under development.

The gravity map gives a good picture of regional trends, and frequently local anomalies, related to individual structures, are found. The gravity work is being used to select the most promising areas and seismic work is being used for detailed surveys.

In the Ebano-Pánuco district, where production is found in fractured areas of limited extent, which in many cases come very close to the surface, both electrical and seismic methods have been used.

The electrical method is being used to detect shallow fracture zones, which

generally continue with depth, and has been a great help in the location of both development wells and wildcats.

The seismic reflection method has been used experimentally to find out if fractures can be detected. The country is generally flat and a good continuity between records can be obtained in great parts of the area where shallow reflections of high frequency have to be correlated. Results have been very promising, as very often the fracture zones show as non-reflecting belts in a good reflection country. The very limited amount of information available on fracture detection based on seismic methods shows a good agreement with well results, but more experience has to be gained before a definite statement can be given.

A great amount of geological and seismic work has been done in the area west of the Golden Lane in a belt extending from Papantla to San Gerónimo. The area is generally hilly with very few roads, has a very dense vegetation and shot-hole drilling conditions are frequently difficult. Furthermore, reflecting conditions are poor in large parts of the area. As a result of this, the work is slow and expensive.

In this area (west of the Golden Lane) the Poza Rica and Moralillo fields are located, and the area is considered one of the most promising portions of the province. Several structures found by Petróleos Mexicanos' studies have been drilled. The information obtained has been very valuable for determining facies distribution in the area studied.

The Presidente Alemán, Tancoco, and Moralillo fields have been discovered in this area as a result of Pemex exploration work.

Geological and seismic work is being currently carried on in the eastern part of the Golden Lane area where some small production was found in the past. A big part of this area is covered by dense vegetation and the terrain is moderately hilly. In general good reflections are predominant in the area and some small structures have been mapped which have good possibilities. So far production has been found in two of the recent exploration ventures, Tamiahua and Solís. The limestone is found to be porous in all the wildcats drilled so far on the east side of the Golden Lane and it is considered probable that many small new fields will be found as a result of the exploration work under development.

Another important work being carried on by Petróleos Mexicanos is the exploration of the southeast extension of the Golden Lane, which is being mapped with the seismograph. The area is extremely hilly and the problem to be solved is to find local closures on the reef, which is plunging very rapidly to the southeast. So far, four wildcats have been drilled in this prospect area, all of which have found good porosity and oil indications, but no commercial production has been found.

Some other areas in the Tampico-Tuxpan province have been explored by geological and geophysical methods and some drilling has been done without discovering any new fields. The present drilling program contemplates the drilling of many new prospects during 1952.

Table 2 shows the new fields discovered by Petróleos Mexicanos in the Tampico-Tuxpan province, and the basis for their location.

Besides the exploration for new areas in the Tampico-Tuxpan province, there has been an intensive drilling campaign based mainly on subsurface geology to search for new pools in the productive areas. This work has resulted in the discovery of new pools, or extensions, at Pánuco, Cerro Asul, Juan Felipe, and Alazán.

Veracruz Embayment

The Veracruz Embayment is limited to the north and south by the Teziutlán and San Andrés Tuxtla massife respectively, and to the west by the Sierra Madre mountain front. This area, of about 30,000 square kilometers, had been studied previously by reconnaissance surface geology and torsion balance, but no production has been found. The province lies midway between Tampico-Tuxpan and

TABLE 2

PRODUCTIVE FIELDS DISCOVERED BY PETROLEOS MEXICANOS IN THE NORTH ZONE OF MEXICO

Name of Field	Disc Year	Basis for Location	Productive Formation	Production
Soledad*	1945	Seismic	Middle Cretaceous	Oil
Tlacolula*	1947	Surface Geol. Seis.	Middle Cretaceous	Oil
Nuevo Limon	1947	Resistivity Seis.	Middle Cretaceous	Oil
Moralillo	1948	Surface Geol.	Middle Cretaceous	Oil
Alazan	1949	Surface Geol.	Middle Cretaceous	Oil
Tenexco†	1949	Surface Geol. Seis.	Middle Cretaceous	Oil
Pte. Aleman	1949	Subsurface Geol. Seis.	Middle Cretaceous	Oil
Tancoco	1950	Surface Geol.	Middle Cretaceous	Oil
Tamiahua	1951	Subsurface Geol. Seis.	Middle Cretaceous	Oil
Solis	1952	Geol.	Middle Cretaceous	Oil

* No commercial fields.
† Temporary abandoned field.
Data completed as to April, 1952.

the Isthmus oil fields, and there is a big development of Tertiary and Cretaceous sediments, in facies similar to those of the adjoining geological provinces.

The area is practically virgin, as only 8 wildcats had been drilled prior to 1951, and only a few good shows have been observed. It is one of the best potential oil provinces in Mexico, where production can be expected in Miocene and Cretaceous formations.

Pemex started exploring this area in 1948 and is currently maintaining two geological parties, one gravitymeter crew, and one seismic party. There is also one drilling rig which is testing the most important structures found in the area. If a new field were discovered in this province there would be an important increase in exploration activities, but work has not reached a point where proper evaluation of its potentiality can be made.

Isthmus-Tabasco Province

This province, where commercial production was found at the beginning of

the century, has in its western part the most important oil fields of southern Mexico, and recently some new gas and oil production has been found in its eastern part.

Practically all production (Fig. 5) from the Isthmus-Tabasco province comes from Miocene sands, and a small part from upper Oligocene sands. However, there are good prospects for Cretaceous production and several wells are being drilled which will test the Cretaceous formations.

With the exception of the western and southern parts of the province, all of it is covered by recent material and is sparsely inhabited. It is very swampy, and it is not possible to use automotive transportation. In general the entire Tabasco area is good reflection country. Most of the area between the Isthmus fields and the Río Grijalva had been covered by torsion balance surveys, and Petróleos Mexicanos has extended the regional gravity survey in all the low land up to the Candelaria river, to serve as basis for the seismic exploration work. In addition to this work gravity surveys have been carried on in the north-central part of Yucatán and in Campeche. This later work is being extended from a regional map which will cover all the area between the Isthmus oil fields and Campeche.

Surface geology surveys have been conducted in all the areas suitable for this type of work.

TABLE 3

PRODUCTIVE FIELDS DISCOVERED BY PETROLEOS MEXICANOS IN THE SOUTH ZONE OF MEXICO

Name of Field	Disc. Year	Basis for Location	Productive Formation	Production
Acalapa	1947	Surface Geology	Miocene Encanto	Oil
Sarlat	1948	Surface Geology	Miocene Amate Inf.	Gas-Distillate
Moloacan	1948	Sub-surface Geology	Miocene Encanto	Oil
Fortuna Nal.	1949	Sub-surface Geology	Milcene Amate Inf.	Gas-Distillate
Tortuguero	1949	Seismic	Milcene Encanto Oligocene Deposito	Oil
Xicalango	1950	Seismic	Miocene Indif.	Gas
Jose Colomo	1951	Seismic	Miocene Amate Inf.	Gas-Oil
Rabon Grande	1951	Seismic	Miocene Encanto	Oil
concepcion	1951	Sub-surface Geology	Miocene Encanto	Oil

Note: Data completed as to December, 1951.

In the western part of the province, where salt dome type oil fields are found, seismic reflection and refraction work has been done, and four new salt domes have been discovered, but no commercial oil production has been established around them.

Part of the continental shelf has been surveyed by marine seismic reflection work and some drilling has been done on the basis of this study. As a result of this survey, commercial production has been found in Rabón Grande and some oil production in Tortuguero. So far those structures drilled are in part covered by the waters of the Gulf of Mexico and part of them are on shore.

Seismic work has been done in large portions of central and eastern Tabasco, and in the western part of Campeche, in a practically virgin territory. Drilling in this part of the country has been retarded so far, but as a result of the combined geological and seismic surveys, commercial production has been established in eastern Tabasco.

Table 3 shows the oil fields discovered by Petróleos Mexicanos in the Isthmus-Tabasco province. In addition to them some new production has been established

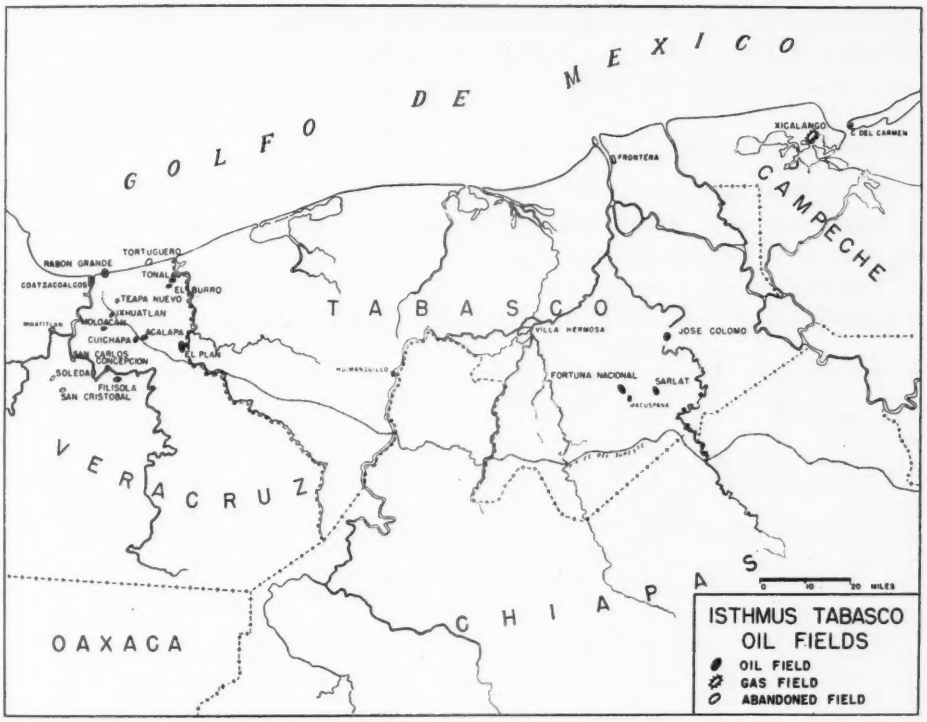

FIG. 5

in El Plan, Nuevo Teapa and Ixhuatlán fields. Recent extension in those fields has been based on subsurface geology.

The general opinion in Mexico is that this part of the country presents very good possibilities for a rapid development and Petróleos Mexicanos has started a very intensive exploration drilling campaign to develop the José Colomo oil field and to test some other nearby structures discovered by the seismograph.

Other Areas

In addition to the work done in the gulf coastal plain, which was described above, geological reconnaissance surveys, and some detailed surveys have been made in other parts of the country. The most important areas studied have been

Lower California, Coahuila, Chihuahua, and Oaxaca. Cretaceous formations seem to be the best prospective oil horizons, but further drilling is necessary in order to know more about the stratigraphy of those areas, because a definite section cannot be established in most of them.

Geophysical work has been done in a very small part of Chihuahua and an extensive gravity survey is under development in Sebastián Vizcaíno desert, in Lower California.

Some exploration wells have been drilled in Chihuahua and Lower California, but no important oil shows have been recorded, although good sedimentary development has been found. In general these two areas are considered to be in their early stage of exploration and new locations are still to be made.

Comparative Intensity of Exploration

There is no system known to the writer, which will determine if the amount of exploration work is adequate to maintain and increase to an adequate level the reserves of a country or a province.

Possibly there will never be such a method, as the discovery of new reserves is related to the quantity of structures or oil traps which are remaining to be

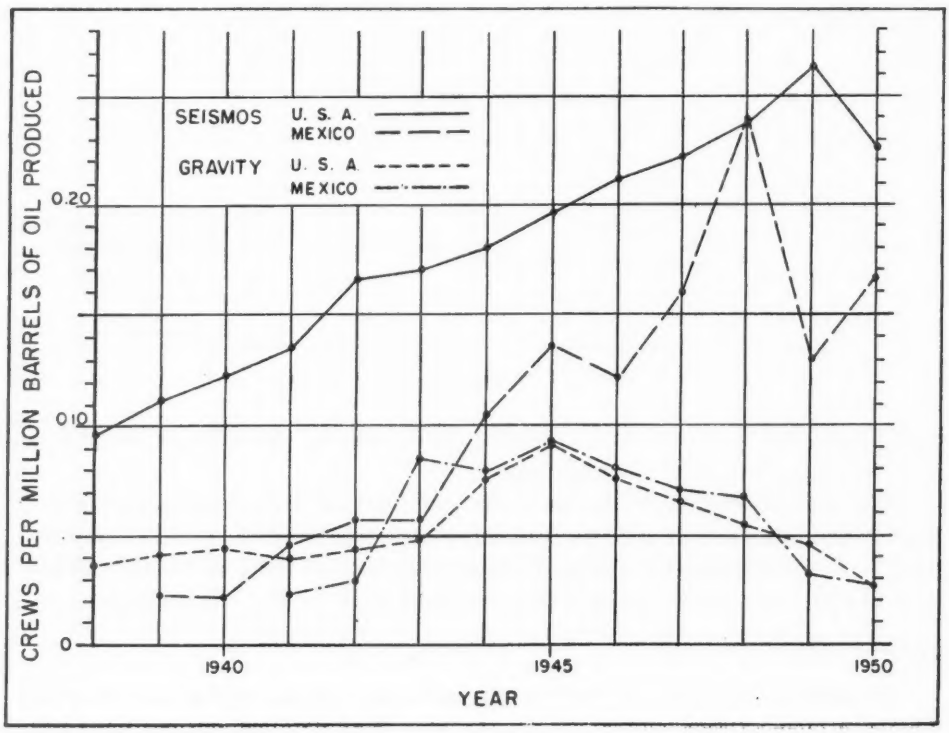

FIG. 6

discovered, and to the knowledge of possibilities of recognizing the typical conditions under which oil is found in the area under consideration. The relative amount of exploration is often mentioned by people interested in the search of petroleum, but no attempt has been made, so far as the writer knows, to define intensity of exploration.

In this paper, in order to compare the intensity of exploration of the United States and Mexico, Table 4 is presented in which the total number of geophysical crews and the total production of both countries are shown.

The intensity of exploration is defined as the number of crews operating divided by the total production of the country. On this basis the relative amount of exploration for both seismic and gravitymeter work is shown in Figure 6.

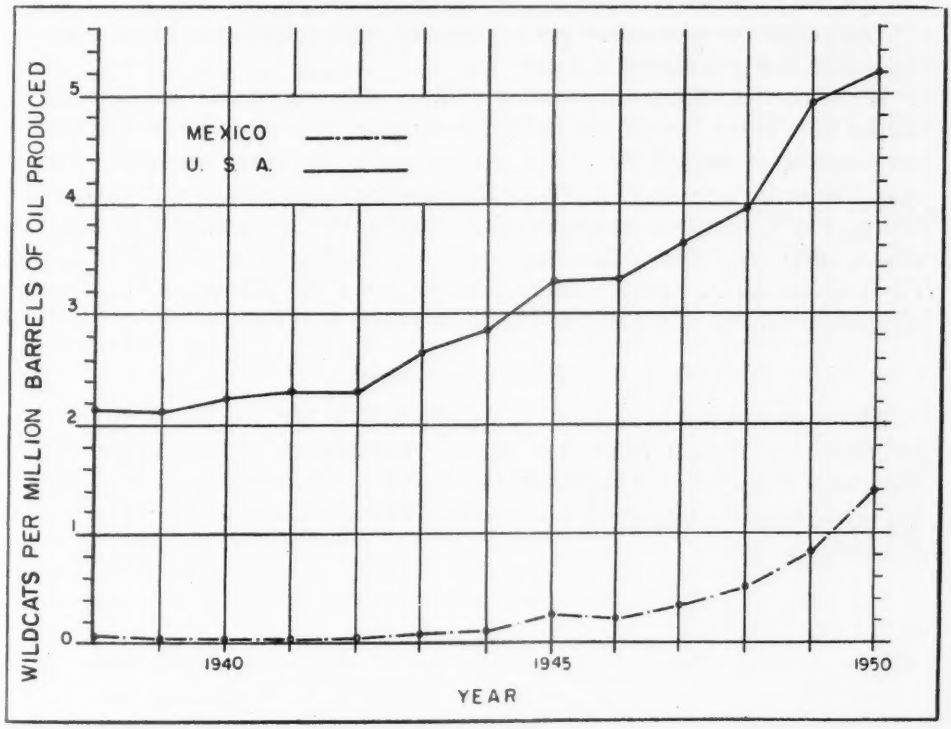

FIG. 7

It can be seen that for the amount of production in Mexico the intensity of seismic exploration has been always smaller than in the United States. However, there is notable a definite increase and a tendency of both graphs to reach the same value.

Without attaching exceptional value to such curves, the writer believes that they give an idea of the exploration efforts of both countries per million barrels of oil produced, but the following points have to be taken into account.

a. The relative amount of exploration should be measured not on a basis of the number of crews, but on the number of stations observed per square kilometer (or mile).
b. There is some amount of duplication of United States seismic surveying effort due to the problems of different companies operating in the same general area, but that difference will compensate in part the problems of mobility in Mexico. Therefore, it is reasonable to say that the intensity of seismic exploration in both countries should be about the same.
c. To have a comparable intensity of gravity exploration in Mexico and the United States, the intensity of gravity work in Mexico should be higher than in the United States, because transportation facilities, and therefore actual coverage, is better in the United States.

The number of exploration wells drilled per million barrels in Mexico and in the United States is shown in Figure 7.

It can be seen that the amount of wildcats drilled in Mexico has been much smaller than in the United States, but the number is increasing very fast and is reaching a level comparable to that maintained by American companies during 1940. The writer believes that Mexico should increase the intensity of exploration drilling, but it should be remembered that the United States level of exploration wells is affected by lease obligations, and a large duplication of effort is involved. This problem does not exist in Mexico and therefore, the difference in the level of exploration drilling is actually smaller than shown in the graphs.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation to Mr. Antonio J. Bermúdez, Director, and Manuel Rodríguez Aguilar, Exploration Manager of Petróleos Mexicanos, for permission to present this paper, and the staff of the Exploration Department for the help given in the compilation of the data and the preparation of figures and tables.

PETROLEUM EXPLORATION ON OUR PUBLIC LANDS*

JOHN R. KILLOUGH†

ABSTRACT

Exploration for oil and gas has soared to an all time maximum, and it will continue to increase. In eleven western states such exploration will be predominantly on our public lands. These lands are managed to (1) conserve and perpetuate natural resources, (2) give greatest good to the greatest number, and (3) have the benefits exceed the cost. The conservation program of the Bureau of Land Management is engaged in the construction of soil and moisture conservation projects, range improvements, and revegetation. At the present time the Bureau is actively engaged in controlling the poisonous invader Halogeton, employing herbicides and reseeding. Seismic methods, as often employed, may be destructive to soil and vegetation or surface resources and therefore opposed to other activities and interests. Direct losses occur through improperly bulldozed trails and the use of stockwater reservoirs. Shot holes left unplugged are dangerous. The oil and gas industry must develop conservation policies within its own ranks. Roads may be properly constructed and damage repaired. The petroleum industry must decide by its own actions its future place on our public domain.

Exploration has attained extremely high levels of importance in the mining field, expecially for petroleum, where current rates of oil and gas production have soared to all-time maximums. Expenditures for exploration, wildcat drilling, geological and geophysical work over the 11 year period from 1937 through 1947 increased more than four times.[1] Nevertheless, only a near-constant value for the ratio of annual production *vs.* proved reserves was maintained during this period.

Looking to the future it is conjectural whether or not the same ratio of annual production *vs.* proved oil reserves may be maintained. It is not a matter of conjecture, however, that exploration activity has increased and will continue to increase. Improvements in the performance of present geophysical apparatus will be effected and the integration of existing exploration methods will be improved, but primarily present methods will be applied in greater intensity. Hitherto unexplored areas will be studied and old areas will be worked and reworked.

Geophysical crews will explore on lands of various ownership. In the eleven western states their work will be predominantly on our public lands, since the bulk of the arid west is public domain.

The "public domain" is the original landed estate of the American people, the property of all the citizens of a great democracy. The original public domain covered three-fourths of the continental United States and all of Alaska, some 1 billion 800 million acres—2 million 800 thousand square miles. Under the disposal policies of the Government approximately 1 billion acres in the United

* Manuscript received by the Editor June 21, 1952. Manuscript solicited by Robert Dyk, of the Public Relations Committee.

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[1] H. J. Struth, "1947 Oil Discoveries Largest Since 1937." The *Petroleum Engineer*, 19 (Jan. 1948), 51–58.

States have been transferred to private owners and the local state governments. Today about 412 million acres are in public ownership in the States and 365 million acres in Alaska.

The Bureau of Land Management is directly responsible for the administration of 191 million acres in the continental United States and 344 million acres in Alaska. This amounts to roughly a quarter of the total land surface of the States and Alaska combined. The Bureau is also responsible for the disposal of mineral resources on 827 million acres of public domain and acquired lands.

More than 95 percent of the present public domain outside of Alaska is located in the 11 westernmost States. The bulk of the lands are rough and mountainous or arid and semi-arid. While little of it is suitable to cultivation, it is an important segment of the American economy, valuable for grazing, timber production, watershed protection, wildlife protection, water supplies, mineral production, power development, recreation, and military use among other values. The government is managing these lands on a multiple-use and sustained-yield basis.

A brief study of the grazing use of the public domain during the 1947 fiscal year shows that permits were issued to 20,960 stockgrowers, covering 2,095,140 cattle, 97,827 horses, 6,546,143 sheep, and 45,217 goats. At the same time approximately 600,000 deer, elk, antelope, and moose grazed on these lands. These figures do not include grazing leases issued to 16,066 operators outside of organized grazing districts embracing over 13 million acres.

Underlying the Bureau's policy in managing the public lands and resources are three basic principles. First, that they be so managed as to conserve and perpetuate the natural resources. Second, there is the principle of priority of public interest, the recognition that these lands and resources are the property of all citizens and that they be so managed as to give the greatest good to the greatest number. Third, that the benefits, regardless as to their nature and to whom they accrue, should exceed the cost.

The conservation and maintenance of the natural resources is, of course, the most difficult principle of this policy to carry out. Frequently the public lands have several uses. Grazing lands may also support timber. Lands valuable in minerals are often valuable also for grazing, recreation, or watershed. The problem arises from the conflict of these various interests.

The conservation program of the Bureau of Land Management not only includes the proper management of the land through regulation of its use, but also the construction of soil and moisture conservation projects, range improvements, and revegetation. For example, prior to January 1, 1949, 1,144,000 acres of range land were reseeded, 108,282 stock water and erosion control dams were constructed, 5,604 miles of contour furrows were made, and 9,250 miles of fence were built among various other practices.

At the present time the Bureau is actively engaged in controlling the poisonous invader Halogeton, which is spreading rapidly and causing livestock losses in Wyoming, Nevada, California, Idaho, Utah, and Montana. The known area of

infestation covers over a million and a half acres and estimates of scattered infestations indicate a much larger gross area. The present control program consists of the use of herbicides on the main avenues of spread such as highway and railroad right-of-ways, seismograph trails, and pipe line right-of-ways (Fig. 1). Along with this temporary method, reseeding, which appears to be the most practical method of permanent control, will be used as extensively as possible. In general the plan of attack is to confine the spread of Halogeton behind defensible barriers. It is estimated, due to the immense area already covered by Halogeton and the

FIG. 1. Halogeton spreads along an oil pipe line right-of-way.

rapid rate at which it is spreading, three million acres may eventually need reseeding.

This is a brief picture of the public domain for which the Bureau of Land Management is responsible. Many activities have not been mentioned, such as sales of isolated and small tracts, homesteads, desert entries, rights-of-way, enforcement of trespass regulations, cadastral surveys, oil, gas and coal leases, timber management, fire suppression, and many others.

Seismic methods employed in oil and gas exploration on the public domain are often destructive to the soil and vegetation or surface resources and are therefore, diametrically opposed to most other activities and interests. Let us examine a few specific examples where seismograph work conflicts with the principles of conservation and sustained yield.

Most seismograph trails are constructed with a bulldozer and average ten feet in width. A mile of such trail covers roughly one and one fifth acre. On grazing lands of average carrying capacity five miles of seismograph trail will destroy the feed required to carry a cow and her calf for one month. If the dozing is done correctly the vegetation will return to its normal productivity within two years. If, on the other hand, the soil is removed below the roots of the grass and other forage plants this trail may remain barren for many, many years, not only depriving livestock of feed, but exposing the soil to the erosive action of wind and

FIG. 2. This dozer trail will produce a new gully, but no beef or wool.

water (Fig. 2). In the Big Horn Basin of Wyoming an estimated 10,000 miles of seismograph trails have been constructed during the past three years. Interpreted in pounds of beef this has meant a loss of 120,000 pounds of beef each year in this small segment of the western states.

Many direct losses of livestock occur as a result of improperly constructed seismograph trails. Dozer operators often fill gullies in order to make roads suitable for trucks transporting exploration apparatus. If these fills are left in the gullies they impound water and become death traps for sheep and cattle which become bogged and die in these shallow ponds of mud and water (Fig. 3).

Livestock must have drinking water in order to graze a range area. This water is provided over most of the public domain by earthen dams. Stock graze out for a radius of one to two miles from these stockwater reservoirs, but if this water dries up or is utilized for other purposes they can no longer graze the area and the forage cannot be used. This means a loss to stockmen of three to six thousand acres of feed worth $1,000 to $2,000 at commercial rates. These ponds are small and seismograph crews hauling water for drilling reduce them from a stockwatering facility to a dangerous bog hole in a few trips with the water wagon.

Stockmen have many other difficulties as a result of geophysical work. Shot

FIG. 3. A death trap for sheep constructed by geophysical crews.

holes left unplugged are dangerous to both livestock and man. The numerous trails make herding difficult since livestock, especially sheep, tend to follow roads and trails and wander away from the desired route. Gates left open or fences down result in the loss of livestock, unnecessary riding, uncontrolled breeding and the mixing of herds, not to mention the cost of maintaining these fences. Seismograph crews have caused the stockmen and others making legitimate use of the public lands much distress by destroying bridges, cattle guards, culverts and established roads with their heavy trucks and equipment.

Looking at geophysical exploration work from a soil conservation standpoint the removal of surface vegetation inevitably results in loss of soil. Seismograph trails in general follow straight lines for miles traversing the range up hill and

down hill, crossing gullies or following them according to the dictates of the survey. Any moisture that falls is picked up in these trails and once concentrated follows the trail like a ditch until it reaches a low spot where it can escape. Erosive action increases with the volume and acceleration of the concentrated run-off water which picks up and carries with it soil particles. Thus, instead of flowing beneficially in thousands of tiny streams over the range as it should, precipitation is gathered by the seismograph trail and runs off in a destructive torrent cutting irreparable gullies and carrying its burden of silt into irrigation ditches, stock-

FIG. 4. This once grassy coulee will be a raw gully with the first rain because of careless dozing.

water dams, and even into multi-million dollar power structures (Fig. 4). Consider the paradox of hundreds of seismograph crews busy stripping the vegetative cover from thousands of miles of virgin range, aggravating erosion conditions, and paving the way for the spread of undesirable weeds and poisonous plants, while the Federal Government and its agencies, local, state, and county governments and individuals are spending millions annually to combat erosion and conserve this nation's soil and water resources.

We of this generation have witnessed in America and in our own communities the most rapid and spectacular conquest of natural resources in history. We have seen natural wealth wasted by legitimate industry in the haste of development. We have explored the last frontiers and had to seek opportunity in lands already exploited. Two costly wars have drained the world during our lives. We are now

contributing a large percentage of our earnings to alleviate the suffering of nations who did not learn the lesson of conservation, and the limitations of our own resources have been made obvious. We are now a conservation conscious nation. Therefore, any practice which may endanger or impair the value of our lands and resources soon becomes a matter of public concern.

Protests against damages caused by the employment of improper practices by geophysical exploration crews are increasing at a tremendous rate. Local groups of stockmen, farmers, and conservationists have passed resolutions aimed

FIG. 5. A contract dozer trail, costly and of doubtful value to the exploration crew —inexcusably destructive to our land.

at reducing these damages. Seismograph damages are being discussed at every meeting of local soil conservation groups, grazing district advisory boards, farm groups, garden clubs, and sportsman's organizations. The obvious trend is toward the introduction of legislation designed toward enforced regulation of geophysical exploration. The enactment into law of proper regulations is not in itself undesirable, however, legislation founded on the anger of damages suffered and the desire for immediate action is often hysterical and illogical.

Meetings have been held recently between representatives of the oil and gas

industry and representatives of the Bureau of Land Management and others concerned with petroleum exploration and the administration of public lands. During these meetings conducted specifically for the purpose of devising ways and means of eliminating excessive damage due to gas and oil exploration, one factor stood paramount—the petroleum industry must recognize the principles of multiple use and conservation on our public lands.

The oil and gas industry can develop conservation policies within its own ranks and fall in step with other public domain users. The first step in this direction is

FIG. 6. A sheer waste of exploration money, since no road was needed over this rolling grassland.

obviously for the industry to make itself acquainted with those groups and industries using the public lands for other purposes, and the agencies responsible for the administration of the public domain. This may be accomplished by attending local group meetings and individual contacts. This will result not only in better understanding among the various users, but will also provide a mutual meeting ground where information may be exchanged and common problems worked out. The second step is the determination of what constitutes proper seismograph practices compatible with the principles of conservation and sustained yield. Thirdly, the knowledge gained through the first two steps must be put into practice on the job. And finally, the oil and gas industry and its associates must see that each and every company, crew, and contractor is fully informed and functioning in a manner beyond reproach by other members of the industry

or other users of our public lands. A hundred good jobs may go unnoticed and lost to memory, but one poor job will never be forgotten.

Many companies are discovering that the use of a tractor and bulldozer may be practically eliminated at an actual saving in operating costs (Fig. 5). These companies are taking advantage of established roads, old seismograph trails, and improved automotive equipment. During wet weather dozer trails are seldom passable since there is no vegetation to give vehicles traction. When a

FIG. 7. Truck marks above and to right of hat indicates the lack of necessity for this trail.

dozer is necessary it is advisable to supervise this phase of the work closely, since this is one of the greatest causes of damage. Bulldozer contractors are not held responsible for exploration damages and are naturally anxious to cut as deep and as wide as possible with their machines in order to spend more hours on each job (Figs. 6 and 7). In addition to better supervision, the writing of contracts may be improved to protect oil companies and seismograph crews against poor dozer work.

Damages to established roads and trails and to the land surface reach the maximum during wet periods. At the same time many unproductive hours are spent by crews searching for passable roads and digging equipment out of the mud. Wear and breakage on equipment also increases with wet muddy conditions. Therefore, the number of hours spent in the field is not a reliable measure of productivity. Unseasonable weather in our arid public domain states is in-

frequent and crews would be saved time, money and difficulty, if field work were suspended during these periods.

A properly constructed seismograph trail leaves the grass roots intact, it is too shallow to intercept run off waters on either side slopes or gullies, and where gullies and brush will allow the passage of vehicles the vegetation and ground surface is not disturbed at all, since no dozer work is necessary (Fig. 8). Some road and trail building cannot be avoided, but when it is necessary surface damages should be repaired, by cutting out gully fills, leveling furrows which may collect water, and reseeding with approved grass species.

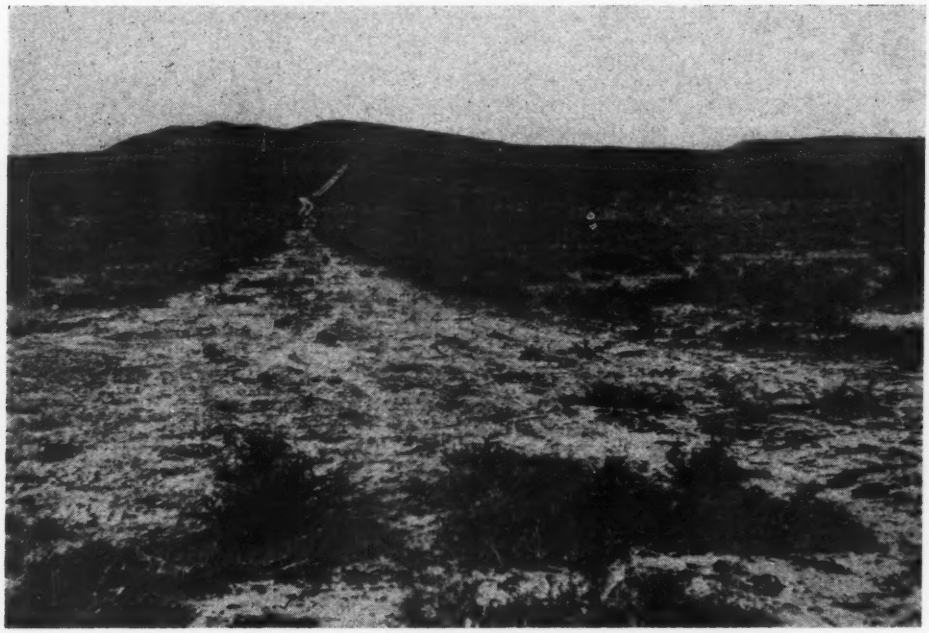

FIG. 8. This is a well constructed trail which does not concentrate water and will soon grass over.

Reseeding cannot be recommended too highly since this is an established practice proved successful by years of experimentation and application. Crested wheat grass is perhaps the most universally adapted species and is further desirable due to its availability and reasonable cost. Several other good species such as Russian wild rye grass, tall wheat grass, and intermediate wheat grass may be used throughout most of the western states. Reseeding on loose soils can be accomplished with an ordinary grain drill or by broadcasting and covering the seed with a harrow, light disk or brush drag. Where the ground surface is packed and hard, seed must be drilled with a grain drill to insure that it is properly covered. Seed should be broadcast or drilled at rates varying from eight to twelve pounds per acre, depending upon whether it is drilled or broadcast, species used, and

quality of seed. The cost of reseeding varies with the condition of the trial, topography, size of the total job, species and seed used, and distance from towns and other facilities, but will average from five to ten dollars per acre. A mile of average dozer trail contains approximately one and one-fifth acres.

Both administering agencies and other users are interested in water on our public lands, since water is scarce and vitally needed in obtaining full use of the surface resources and in the proper distribution of domestic animals and wildlife. Information as to the location and depth of water which may be encountered in shot holes is extremely valuable and will be received with appreciation.

These are a few measures which will improve the quality of geophysical exploration and make seismograph crews more welcome on our public lands. Most industries and individuals making use of the public resources do so under rigidly written and enforced regulations. The mining industry (except for certain types of leases such as coal and oil and gas leases) has always operated under liberal laws and few regulations. Oil and gas explorations have been conducted on an honor system with no specific regulations. Disregard for the public interest and abuse of our national resources is tipping the balance, and the petroleum industry must now decide by its own actions its future place on our public domain. Will it choose conservation and voluntary cooperation or legislation and enforced regulation?

CONTRIBUTIONS

The following letter has been received by B. G. Swan and Adrian Becker with reference to their paper "Comparison of Velocities Obtained by Delta-Time Analysis and Well Velocity Surveys," which appeared in the July 1953 issue of *Geophysics*.

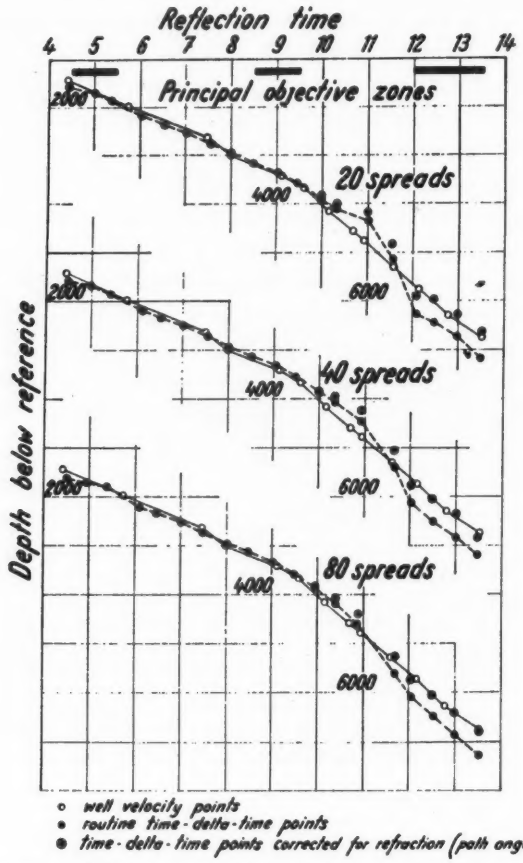

Fig. 9 of the paper of B.G. Swan and Adrian Becker, completed by correction for refraction (path angularity)

Dear Sirs:

With great interest I have read your paper "Comparison of Velocities Obtained by Delta-Time Analysis and Well-Velocity Surveys" and I admire the great accuracy which you obtained by your method.

Now I have recently dealt with the question whether or not the influence of refraction or as you call it—the influence of path angularity is of importance for those examples you have shown. In solving this problem I used the method described in my paper "An Approximate Correction Method for Refraction in Reflection Seismic Prospecting," page 479–484, *Geophysics*, 1951, No. 3. As perhaps you may be interested in the results I beg to communicate them to you.

In the figures 3–8 the correction which has to be applied is less than 2.5 percent. In the deepest points of figure 3 1.5 percent is attained in those of figure 8 2.5 percent. In all other cases the correc-

tion does not exceed 1 percent so in figures 3–8 it is not worth taking account of the influence of refraction (path angularity). By the way it may be mentioned that the correction we are dealing with is always negative—that means that in reality the depth is smaller than according to routine delta-time-analysis.

In figure 9, however, the correction is considerably higher than in the preceding examples. Here up to 7 percent are attained. In the figure enclosed in this letter I have therefore added those points which are obtained by using the corrections for refraction (path angularity). As will be recognized the agreement between corrected time-delta-time-points and well-velocity-points is surprisingly good, especially between 1.15 and 1.35 sec.

As perhaps the contents of this letter is interesting for the readers of *Geophysics* I add a copy of this letter and if you have no objections I beg you to send this copy to the editor of *Geophysics*.

Yours sincerely,
TH. KREY
Seismos G.m.b.H.
Hannover, Germany.

REPORT OF THE XIX INTERNATIONAL GEOLOGICAL CONGRESS

ABSTRACT

A report of the XIX International Geological Congress held in Algiers, Algeria, is presented, and the abstracts of twenty-nine papers on geophysics presented at the meeting are submitted.

The XIX International Geological Congress held at the University of Algiers was formally opened in Algiers, Algeria on September 8, 1952, and it was closed on September 13, 1952. The meetings were preceded by forty excursions to geologically interesting areas in Algeria, Tunis and, Morocco. These same field trips were to be repeated immediately after the Congress in addition to an extended trip through French West Africa, provided there would be sufficient subscribers.

The registration of the attending Congress members started on September 1, although the major influx of registrants was on September 7, when the pre-Congress excursion members began to arrive in Algiers. A total of 1,500 geologists from all parts of the world attended the meetings.

The attending and subscribing members of the congress received or will receive the following: geologic maps of North Africa, Morocco, northern Algeria, detail maps of local areas of interest, guide books of the North African excursions, and books of the papers presented at the meeting.

A total of over 360 papers were submitted to the Congress and presented at the meetings of the following fifteen sections:

I—Pre-Cambrian
II—Paleozoic
III—Rock deformation
IV—Sub-marine topography
V—Fossil man
VI—Vein deposits
VII—Deserts
VIII—Hydrology
IX—Geophysics
X—Iron deposits
XI—Phosphate deposits
XII—Applied Geology
XIII—General Geology
XIV—Petroleum fields
XV—Paleovolcanology

In addition to the above general divisions, the meetings of the following groups were held concurrently, and papers presented:

Report of the Pliocene—Quaternary

The Africa Geologic Services
Gondwana Commission
International Paleontological Union
International Commission on Clay Study

The official languages of the Congress were English, French, and German. However, the papers were presented to the attending Congress members in the language with which the author was most familiar. The majority of the papers were in French.

The following are the abstracts of the geophysical papers presented at the XIX International Geological Congress:

"Correlation of Gravity and Magnetic Observations with Geology of Blanco and Gillespie Counties, Texas," by Virgil Barnes, Warren A. Anderson, and Frederick Romberg.

A gravity survey was made of a 2,000-square mile area in central Texas where the pre-Cambrian basement rocks are mostly covered by Paleozoic and Mesozoic sedimentary rocks up to a mile in thickness. The variation in gravity found is related to the buried pre-Cambrian rocks, which vary in density from granite (2.62) to schist (2.95) and to basic igneous rocks, some of which are even denser.

Structure in the sedimentary rocks and buried topographic features on the old pre-Cambrian and pre-Mesozoic erosion surface undoubtedly exert some influence on the gravitational force measured, but this influence is too small to be recognized in a regional survey of the type discussed in this paper. However, sufficiently detailed gravity surveys should make it possible to detect some of the buried topographic features.

The magnetic data, while not entirely conclusive, indicate that granite and schist produce only small anomalies and that strong positive anomalies are associated with areas of basic igneous rocks.

"Cinq années de prospection électrique en Afrique du Nord pour les recherches hydrologiques" ("Five years of Electrical Prospecting in Connection with Hydrological Investigations in North Africa"), by J. J. Breusse.

A map giving the statistics for North Africa shows the geographical locations of the hydrological studies. A summary tabulates the number and duration of the prospecting performed until December 31, 1951 for Tunis, Algeria, and Morocco. The data from the problems investigated in these three areas are given. A typical example is given for each region showing the results of the geophysical investigations as well as the results obtained from subsequent drilling.

Tunisia: The water table is studied in connection with the behavior of the water bearing strata and the delineation of the faulting. A study is made of the upper beds of the Pliocene and Pleistocene in order to determine the sweet water distribution.

Algeria: A study is made of a region of dunes to determine the thickness of the sands and to delineate the iso-piezometric lines in the search for more permeable zones. A study is also made of the alluvium of a littoral plain together with the distribution of salinity and the location of the feed zones of this salt water. Stratigraphic and tectonic studies are made of a closed basin (Chott). The behavior of a deep water bearing sand is determined.

Morocco: A study is made of the tectonics of a water bearing limestone underlying Tertiary cover. The contouring with depth of the contact between sweet and brackish water of a littoral plain is studied. A contribution is made to the general tectonics of the great plains and to the investigation of their principal structural features. An alluvial stratum is studied to determine its drainage. A quartz schist series covered by recent sediments is studied by geophysical methods.

The number of these studies which is a function of the results that were obtained proves the value of the services rendered by geophysical prospecting for water, and the fact that more and more recourse shall be made to it as is the case in the search for oil where its usefulness is no longer a subject for discussion.

'An Approach to the Rift Valley Problem," by Byron Britton Brock.

Both keystone and compressional theories are challenged; a fresh approach shows the history of Africa to be one of vertical tectonics incompatible with regional compression, and not requiring regional tension apart from general relaxation. The essentials are deep seated steep faults often dating back to pre-Cambrian times. The same fault planes were used repeatedly since.

The dropping of the fault blocks has a counterpart in the upthrust of adjacent blocks, suggesting in each case a limited reservoir of magma below, allowing the principle of the hydraulic jack to operate. Extrusion of lava is an imperfection in the hydraulic device.

Uplifted blocks within the axes of rifts are explained by this principle. Isostasy is irrelevant, and gravity anomalies in the rifts have not the significance hitherto attached to them.

The rift valleys are a part of the general scheme, which includes block faulting and basins and rims all of which involve similar tectonics with a different fault pattern.

"Radiation Logging," by Paul Charrin.

This paper deals with the historical developmental phases of Gamma Ray and Neutron well logging. This is the only method by which geological information can be obtained after a casing has been set in a well. It also gives valuable information in open holes.

Chronological outline of new developments in this well logging system are set forth—including the most recent improvements: Simultaneous Radiation Logging, which enables all radiation logging information to be obtained from a single run in the well; Pure Neutron Logging which gives a better definition of geological strata.

Examples of applications in oil fields are given.

"*Anomalies isostatiques négatives des bassins sédimentaires. Eassai d'interprétation de la carte isostatique du Bassin Parisien.*" ("Negative Isostatic Anomalies in Sedimentary Basins. An Attempt at the Interpretation of the Paris Basin"), by S. Coron.

The Airy hypothesis of isostatic compensation is applied to light masses situated below the level of the geoid. This type of phenomenon counteracts the superficial effect of the surface sediments and varies with the form of the sedimentary basins, and with the depth at which compensation is achieved. This "correction for compensation sediments" is applied to a map showing the isostatic anomalies of the Paris Basin in conjunction with known geologic data. It appears that the residual anomalies would outline major lines of deep structure, thus the continuation of the Hyrcinian structures and their position with respect to recent anticlines and the various irregularities of the sedimentary basin.

"Gravity and Magnetometer Surveys for Chromite Ore Deposits in Turkey," by Kazim Ergin.

The first magnetometer survey for chromite ore deposits in Turkey was done by J. J. Breusse at the Guleman mine in 1941. Positive vertical anomalies of more than 1,000 gammas were measured over the outcropping ore bodies.

During the summer of 1951, M. T. A. Enstitüsü has undertaken a joint gravity and magnetometer survey at the old chromite mines at Ücköprüler and Zimparalik in the Il of Mugla. Bronzite-dunite and bronzite-harzburgite constitute the country rock. Positive vertical anomalies of the order of 2,000 gammas or more were encountered over chromite outcrops. A vertical magnetometer survey has been carried out around old workings and later it was extended northward, following the trend of the anomalous area. Several magnetic anomalies were obtained. Drilling on one of the anomalies has given successful results. At two different depths, ore bodies, each one about 4 meters, were cut. In addition a gallery that went under the same anomaly proved that there was a chromite ore which extended 14 meters in the horizontal direction. A portion of the area that was covered by magnetometer survey was also surveyed by gravimetric method. The results of two methods check fairly in spite of the extremely rugged topography.

The results of two other magnetometer surveys are also discussed in the text. Although the Ücköprüler survey has proved that the magnetometer can be a very useful tool in locating the chromite ore deposits, it is pointed out that there are good reasons for not generalizing this result.

"*Étude géophysique de la fosse bradanique*" ("Geophysical Study of the Bradanic Syncline"), by Facca, Jaboli, Selem, and Roger.

In Southern Italy, the Murge is a faulted plateau of Cretaceous limestone, and repressnts the piedmont of Appenine folding (Alpine type). Between these two regions, there exists a depression which Migliorini (who pointed out its interest from the point of view of oil) called "Fossa Bradanica." It is covered by Pliocene sediments.

The A.G.I.P. has performed in this interesting region gravimetric, telluric, seismic-refraction, and reflection surveys. It has drilled three holes, and a fourth one is in the process of being drilled. The results of all the work that has thrown light on the questions of general regional geology are presented. As a whole, it can be said that from the Murge to the Appenines, the underlying limestone deepens by means of a series of faults. These faults produce a series of horsts and grabens, the trends of which follow the Appenine trend. These are normal faults indicating a tension type of structure. Other less important fault lines, perpendicular to the preceding ones, have Tyrrhenian trends. The comparison between gravimetric, telluric, and seismic results is interesting. These three methods gave excellent results all of which are in perfect accord.

"Radon and Helium in Natural Gas," by Henry Faul, G. B. Gott, G. E. Manger, J. W. Mytton, and A. Y. Sakakura.

Radon has been discovered in some of the helium-bearing natural gas in the United States. So far, the radon content of about 500 producing wells has been explored. Concentrations up to 500 $\times 10^{-12}$ curies per liter (S.T.P.) were observed. The more highly radioactive wells are clustered in several groups. Measurements of radon content under conditions of transient gas flow and theoretical analysis of steady-state conditions indicate that the radon originates in the immediate vicinity of the bore in most wells. This result is tentatively confirmed by gamma-ray logs in two wells, but so far it has not been possible to obtain adequate samples of the gas-producing beds. A few grains of uraniferous solid hydrocarbon have been found disseminated in several drill samples of dolomite from above the gas-producing zones. At the present time, it is not clear whether the radon concentration is sufficient to explain the high helium content of the gas. The research continues, and comprehensive studies of subsurface geology and reservoir characteristics of the gas field are in progress. Most recent results will be reported to the Congress.

"*Étude géologique et géomagnetique du massif du Serpont (Ardennes belges)*" (Geologic and Geomagnetic Study of the Serpont Massif, Belgium Ardennes), by Constantino Gaibar-Puertas and Edmond L. L. Hoge.

The authors describe the geologic and geomagnetic survey made in 1951 in the region of the Paleozoic Serpont massif. Strong magnetic anomalies were found during the survey, and the observations in the area permitted the drawing of a new geologic map of the region. Borings are now being made and their results will permit the authors to establish relations between the geology and the magnetic anomalies found in the region.

"*Champ de pesanteur et déformations quaternaires dans le NW algérien*" ("Gravity Field and Pleistocene Deformations of Northwest Algeria"), by Yves Gourinard.

Geological study of the Oranian shore has shown the existence of a number of Pleistocene deformations. A study of gravity data shows that some of these should be found in regions of isostatic nonequilibrium, whereas others are situated over the massifs which are compensated (these form two groups of connected flexures).

The interpretation of the first type, in the light of preceding geologic events, leads to ideas which fit into the frame of known facts.

The second type, on the contrary, leads one to assume positive vertical motion of the compensated relief, the amount of motion being proportional to the local thickness of the "crust." From this it seems to follow that the generally accepted succession of Pleistocene terraces is the resultant

of eustatic glacial movements and of an over-all rise of the continent. Since this rise has a variable amplitude from place to place, the "levels" that have been established appear to be valid only in the zone of isostatic equilibrium where the "crust" has normal thickness. Since this zone is of great extent, and since in general the crustal thickness must vary but little from its average value, these "levels" which have been established can nevertheless be considered as a satisfactory first approximation. The generalization of these results would be premature at this time and does not always seem possible.

"*Les glaciations quaternaires, les rivières et les anomalies de la pesanteur sur la plaine européene*" ("The Pleistocene Glaciation, the Rivers and the Gravity Anomalies of the European Plain"), by Bronislaw Halicki and Tadeusz Olczak.

The relation between geological and geomorphological processes and the distribution of gravity anomalies has often been discussed without, however, ever arriving at a definite solution to this problem. Recent positive and negative epeirogenic movements have been noticed both in regions of negative and positive gravity anomalies.

The authors analyzed the distribution of Nordic neo-Pleistocene glaciations of the European plain. The delineation on a gravimetric map of the limits of extension and of the areas of retreat of the glacial cover proves that there is an intimate connection between these zones and the distribution of these positive and negative zones or anomalies. This correlation is particularly striking in those areas where one does not find any morphological control of the ice movements. For example, the ice sheets of the last glaciation and of the Warta stage retreat in areas of positive anomalies and advance southward into regions of negative anomalies.

A study of the hydrology also shows that in many cases there is excellent correlation between the character of fluvial valleys and the structure of the gravity field. The aforementioned facts suggest that the major gravimetric provinces have played an important role in the development of geological processes as well as geomorphological evolution throughout Pleistocene time.

"An Interpretation of the Gravity Anomalies in the Eastern Mediterranean," by J. C. Harrison and R. W. Hey.

The results of the 1950 British submarine gravity survey are interpreted together with the relevant measurements of other observers.

The large positive isostatic anomalies in the southern Aegean Sea, and the large negative anomalies lying to the south of an arc running from the Peloponnesus through Crete into Turkey are interpreted in terms of vertical displacements of a crust of almost uniform thickness. The large positive anomalies in Cyprus indicate the presence of an immense basic intrusion; its shape is deduced from the gravity data. It is suggested that here subcrustal matter was forced to the surface of the crust during a period of downward displacement and that it then solidified. The subsequent evolution of the island is discussed on this hypothesis. The positive anomalies on the Nile Delta are examined on the basis of sediment thicknesses deduced from topographical considerations and estimates are made of the crustal depression caused by the sediments. The Malta area is discussed in terms of a southward extension of the structures observed in Sicily.

"*Aperçu sur les travaux effectués en Belgique dans le domaine de la géophysique. Contributions qu'ils apportent à la géologie*" ("Summary of the Geophysical Work done in Belgium. Contributions of this Work to Geology"), by Edmond Hoge and Leon Lambert.

The author summarized the different investigations that have been performed up to the present in Belgium in the field of gravity, terrestrial magnetism, and seismology. He shows the conclusions that can be drawn from these studies concerning the structure and composition of the sub-surface in Belgium.

"*Résultats géologiques basés sur quelques récents profils sismiques-réflexion en Allemagne*" ("Geological Results of Several Recent Reflection Seismograph Profiles Obtained in Germany"), by Krey, Roepke and Wendt.

Recent results obtained by the reflection method are disscussed with their geological interpretation.

The existence of structures in the Keuper salt of northwestern Germany is of particular interest. These structures are situated between the salt domes. Similar structures owing their origin to differences in the thickness of Zechstein salt have been the cause of the discovery of new oil fields.

Interesting results have also been obtained by this method in the coal bearing basin of the Ruhr (which has a Varician trend) and in the Muensterland to the north of this basin. Numerous faults have been discovered whose ages are either earlier than the upper Cretaceous or later. Quite often it has been possible to recognize the folded nature of the Carboniferous sediments.

Finally, interesting reflections were obtained from profiles laid out in the bottom of mines situated in sideritic regions of the Siegerland. These profiles aided in the discovery of new ore veins.

"Applications géologiques d'études sur les microséismes à Alger" ("Geologic Application of Microseismic Studies in Algiers"), by Jean-Rene Lacaze.

Microseismic waves have a meteorological origin: those which are due to surf action along a coast line are of less interest than those originating in the open sea in connection with active cold fronts. The determination of the degree of activity of such a front may be determined by means of a critical study of meteorological data.

In Algiers, the synoptic phenomena associated with cold fronts which produce appreciable effect are either of Mediterranean origin (western basin) or of Atlantic origin. A study of microseismic spectra reestablished known results on the effect of distance on the front from the station with the exception of the Atlantic regions, other than that off-shore of Morocco. In trying to explain this discrepancy, the authors were led to the conclusion that it was due to differences in structure of the oceanic bottom (constitutional rather than structure). The authors criticize certain theories; a qualitative explanation is proposed together with a system of measurements which could perhaps serve as a basis for a theory susceptible to numerical applications.

Also, in the case of the Algiers station, it has been possible to detect the existence of microseismic barriers having a geological nature. The first is in the SSE part of Spain, and might coincide with an outstanding surface outcrop of the African shield (after M. Glangeaud). The second is in the eastern part of Algiers and could be a surface of geological discontinuity, the nature and location of which are perhaps not yet quite clear.

"Sur l'isostasie et l'eustatisme" ("Isostasy and Eustatism"), by Jean Lagrula.

The variation of sea level in the oceans as a function of the variations of volume of continental ice are considered at first in the light of two hypotheses, each of which represents a limiting case.

1. These phenomena occur slowly enough to allow the continuous preservation of isostatic equilibrium.

2. The melting of the ice is instantaneous, and isostatic equilibrium is brutally ruptured and slowly readjusts itself thereafter (isostatic readjustment).

The real phenomenon as it can be deduced from the publications of the Helsinki Isostatic Institute would occur in some fashion intermediate between these two hypotheses.

Areas are considered for which the amount of ice has not varied (Africa for example); the manner in which a stationary level (maximum) such as one which would be associated with a beach line could be achieved. A numerical computation of the elevation of such a level is performed.

A remark is made on a particular level; that which corresponds to the total absence of ice and isostatic equilibrium. A numerical calculation of the elevation is given.

"Sur l'extension au Sahara du réseau gravimétrique nordafricain" ("The Extension into the Sahara of the North African Gravity Network"), by Jean Lagrula.

A summary is given of the North African gravity work. A map showing the isostatic anomalies is given (anomalies are computed on the basis of the Airy hypothesis with the depth of compensation at 60 kms.).

Recently surveyed lines of gravity measurements in the Sahara:

1. El Golea, In Salah, Arak, Tamanrasset, In Guessam.
2. Colomb Bechar, Beni Abbes, Adrar, Reggane, Bidon 5.
3. In Salah, Aoulef, Adrar.
4. Béni Abbés, Oglat, Beraber, Tabelballa.

The difficulties arising in the calculation of precise isostatic anomalies in the Sahara are described. Provisional anomalies and their precision are given.

The following are described: general character of these anomalies; extension to a vast territory of the correlation between the iso-anomaly and structural contours which had been previously established in Algeria and Tunisia: remarks on the depths of compensations; a few remarkable singularities.

"*Possibilités d'utilisation d'ondes transverwales dans la sismique appliquée*" ("The Possibility of Using Shear Waves in Applied Seismic Prospecting") by Linsser.

Shear waves have been observed at times in prospecting seismology. However, these waves have not been utilized rationally in the seismic method. The author points out some of the possible applications.

A method of generating shear waves is described. The laws of propagation of such waves in a homogeneous medium is discussed. Citing two examples, the author shows how faults may be geologically interpreted precisely by the application of Poisson's ratio.

Shear waves will give reflections in heterogeneous media under conditions where compressional waves will not give reflections. The transformation of compressional and shear waves at the contact between two media can provide invaluable information as to the precise location of the discontinuities.

Finally, a study is made of the absorption of shear waves. It is shown how a structure may be delineated by means of the absorption differences, even in those cases where the differences in propagation velocity are too small to allow one to make such a study.

"Magnetic Properties of Basement Rocks," by Asger Lunbak.

Modern accurate gravity observations and observations of magnetic vertical intensity in the same area allow computations of magnetic properties of basement rocks. The principal assumptions to be made are that the layers above the basement do not contribute essentially to magnetic anomalies at the surface of the ground, and that the density of the layers above the basement is uniform and differing from that of the basement rocks.

From such assumptions it is concluded that the mean intensity of magnetization (remanent plus induced magnetism) of basement rocks, in Denmark, Netherlands, and the U. S. A., are of the same order of magnitude, namely from 0.5×10^{-3} to 3×10^{-3} cgs units. This confirms the idea that the intensity of magnetization of granite in unweathered basement is greater than the intensity of magnetization of granite at the surface of the ground.

While the magnetic inclination of the basement rock in a selected area in the U. S. A. (76° W., 36°–37° N.) has shown to be great—like the inclination nowadays at the ground-surface—the magnetic inclination of the basement rocks in Northern Netherlands and on the Danish island Seeland has been shown to be small and clearly smaller than the inclination nowadays at the ground surface. Further, the direction of the magnetic horizontal component of the basement rocks in the two last mentioned areas has been shown to be westerly, i.e., not northerly as now. This indicates the existence of an ancient (possibly early Paleozoic) "northern magnetic pole" near Central America.

"*Étude sur l'évolution d'une ancienne lagune, par la mesure de la résistance électrique spécifique du terrain*" (The Evolution of an Old Lagoon as Deduced from Specific Resistivity Measurements), by Masatugu Murakami.

The Hino-gawa River alluvia brought down from Mount Daisen form flat beach zones with the Yomigahama Bank west of the river estuary on the Japanese Sea.

A detailed knowledge of the sedimentary stratifications deposited by the Hino-gawa has been obtained by a very detailed study of the soil resistivity of all sections of the river's alluvial fan.

The succession of strata from top to bottom generally consists of gravel, sand, and sandy clays. In those spots where there had previously been a lagoon covering a restricted area, argillaceous sands are noted, and the level of the water table is close to the surface. The evolution of the ground forms beginning with the first stages of a lagoon and ending with the formation of today's plain by the continuous accumulation of alluvia has thus been completely elucidated.

"*Distribution des élements radioactifs dans les roches éruptives*" ("Distribution of Radioactive Elements in Igneous Rocks"), by Edgard Ezra Picciotto.

Nuclear photographic techniques have enabled the authors to determine accurately the microscopic distribution of Uranium and Thorium in igneous rocks. The acid rocks are characterized by a very uneven distribution of the different types of radioactive elements among the various minerals. One granite sample shows a very obvious localization of the radioactive elements in the interstices between minerals. Basic rocks show a very homogeneous distribution.

Petrologic and geologic applications of the methods are discussed together with the possible consequences of these studies on the methods of absolute age determination.

The method can also be extended to the geo-chemistry of non-radioactive elements and a few examples are given.

"*Trois cartes géophysiques du bassin d'Aquitaine. Zone sud*" ("Three Geophysical Maps of the Aquitaine Basin, Southern Zone), by Régie Autonome des Pétroles, Société Nationale des Pétroles d'Aquitaine et Richard et Beaufort.

The authors give an outline of the major geological features of the Aquitaine basin. A brief historical survey of the geophysical studies done in southern Aquitaine is presented.

An analysis of the stratigraphy is given from a three-fold point of view: gravimetric, electric, and elastic. The principal types of structure are enumerated.

From the comparison of these "parameters" and tectonic data, the three maps, gravimetric, electric or telluric, and seismic, are described and compared in an effort to determine the advantages and disadvantages of each method.

Conclusions are drawn on the efficiency and utilization of these geophysical methods in a sedimentary basin.

"*La séismicitie de l'Algérie*" ("Seismicity in Algiers"), by Jean Pierre Edmond Rothé.

Numerous earthquakes are felt each year in Algeria, and a steadily increasing volume of data is being amassed at the Institut de Meteorologie et de Physique du Globe d'Alger. The author presents a map on which seventy-two Algerian epi-centers have been accuractely located.

These epi-centers follow the axes of the principal anticlines of the coastal mountains, and of the interior Tell, and the Saharan Atlas; the frequency of the earthquakes is higher in the case of the younger folds. A number of the more important shocks are accompanied by a long series of aftershocks; as for example in the case of the Kerrata earthquake (1949) in the Babors. Every thirty or forty years an earthquake of magnitude greater than six (energy greater than 10^{23} ergs) may occur at some point along these active regions and may result in considerable damage. The towns of Oran, Tenes, Cavaignac, Mascara, and Miliana in the coastal mountains, and Constantine and Guelma in the Tell, are either in the vicinity or on top of active anticlinal zones, and therefore their geographical location may be quite dangerous. It will be of value to draw the attention of the administrators and architects to the Algerian seismicity in order that the proper precautions may be taken.

"*Études par sondages électriques du bassin miocene du Nord du Gharb*" ("Studies of the Miocene Basin of Northern Gharb by Means of Electrical Soundings"), by Société Chérifienne des Pétroles, Aynard et Arnaud.

In the northern Gharb, a three thousand to six thousand foot Miocene series overlies a pre-Riffian

nappe. Undulations in this nappe after its formation could have resulted in the formation of closed structures in the lower levels of the Miocene.

A direct study of these structures is difficult even by the seismic method, so it was found necessary to solve the problem by a more expedient method, namely that of electrical sounding.

This method is indirect, but if one assumes that the Miocene series is conformable, then it is sufficient to determine the structure of one of the upper levels of the series. It so happens that the upper Miocene, which is mostly sandy and has a high resistivity, is very easily distinguished from the middle and lower Miocene, which are marly and highly conductive. This electrical logging method enables one to follow the base of the upper Miocene. The contact could be followed at depths to the order of 800 meters.

In a first reconnaissance, the area was covered by means of one log for every four square kilometers, which enables a coverage of 200 square kilometers per month by a small party. Particularly interesting areas were studied in greater detail.

A series of drill holes showed the accuracy of the method. The correlation is good in the regions where the contacts between the marly and sandy Miocene is sharp. In other areas where there is a transition zone between the two, a fairly good qualitative correlation was observed. It was found that the logging method yielded slightly exaggerated dips.

"*Étude sismique du front de la nappe prérifaine*" ("Seismic Study of the Pre-Riffian Nappe"), by Société Chérifienne des Pétroles, Aynard and Lepetit.

As a result of the 1948–50 drilling, it became apparent that along the front edge of the pre-Riffian nappe, the overlying marly Miocene may contain lenses which could possibly be oil-bearing.

A series of seismic profiles were run normal to the nappe front. The shot holes were drilled every 250 meters with a 21 meter interval between seismometers. The records from this set-up were carefully studied so that no dip data would be lost. On the same recording were noted from sub-horizontal beds coming from the base of the Miocene, as well as reflections associated with extremely large dips. These latter reflections in some cases would intersect the first series on the record, but they could be distinguished due to the excellent quality of the records.

The interpretation of these reflections was made possible due to the direct velocity determinations. These velocity determinations showed that to a first approximation the Miocene and the Cretaceous of the pre-Riffian nappe, both marly, were seismically indistinguishable.

Nevertheless, a study of these cross sections, together with geological considerations, made one feel that in general the nappe was characterized by higher velocities near its frontal edge. This was confirmed by a velocity log (KC-6).

Speaking generally, the results of the drilling have confirmed the fact that beneath the Miocene the front edge of the nappe forms a sort of "crease" structure, the position of which was predicted from the seismic surveys to within a few hundred meters.

"*Étude sismique du bassin jurassique de Petitjean*" ("Seismic Study of the Petitjean Jurassic Basin") by Société Chérifienne des Pétroles, Aynard, Vallet.

In 1949–51 a seismic crew made a study of the region situated between the outcropping Jurassic structures of the region of Petitjean and the granitic outlier which was known to exist about 10 kms. to the northwest (from core holes). This area is overlain by 1500–2,500 meters of Miocene and Cretaceous belonging to the pre-Riffian nappe.

This narrow basin has been studied in detail using a one kilometer seismic grid. The interval between shot holes was reduced to 200 meters in order to make sure that no steeply dipping surfaces would be missed. The depth of the shot holes was of the order of 80 meters in order to penetrate to the marls.

The structural perturbations due to the nappe were a lot smaller than expected. It must be said that the nappe in this region has a regular and stratified character. The velocity determinations in

the hole show that from the seismic point of view it is very similar to the Miocene in these regions.

It was possible to delineate:

1. Large structures which separate the Jurassic basin from the crystalline outlier.
2. Wedge-like unconformities in the Upper Cretaceous.
3. A series of inverse faults in the Upper Cretaceous situated in front of the visible structures. An 'inferior ripple' completely overlain by Miocene was found and followed for about 20 kilometers.

It was shown that in these various structures the Jurassic may be either conformable or unconformable with respect to the Miocene. The various conclusions have been confirmed by the drilling.

"*Étude tellurique dans le bassin de Hodna*" ("Electrical Study in the Hodna Basin"), by S. N. de Recherches et d'Exploitation des Pétroles en Algérie, Bouchon.

The prospecting done in the eastern part of the Hodna basin provides an example of the results of the telluric method in the case of a sedimentary basin.

From the geologic point of view this basin is of interest because there is some lower Eocene along its northern edge which dips southward under a Miocene cover.

A seismic study to outline the structures of Chouf Djelf and of Chott el Hammam, showed that the sedimentary series thinned progressively from the northern edge in the direction of the Chott el Hammam structure. Unfortunately, the zone situated immediately to the north of the Chott el Hammam did not give any deep reflections so it was not possible to follow the various horizons in a continuous manner, nor was it possible to predict the formations which would be encountered if one drilled a hole in the vicinity of the Chott el Hammam.

A preliminary telluric reconnaissance of the structure showed that it coincided with a larger telluric anomaly than one would expect to find in conjunction with a regular fold the size of the one at Chott el Hammam. It was necessary to assume that another effect was being superimposed on that of the Chott el Hammam anticline, and that the resistive sub-stratum was situated at a relatively small distance below the region of high telluric currents. A hole in that region confirmed this point of view.

The telluric map showed high relief which indicates that the thickness of the conductive sediments (Miocene-Eocene and probably partly Cretaceous) is very variable in the Hodna basin, and thin, except for a very small area. Together with the results obtained from coring, this telluric study will give a new orientation to the future search for oil in the region.

"*Analogies géominières entre quelques gisements métallifères en Toscane*" ("Geophysical Analogies between a Few Metallic Deposits in Tuscany"), by Arnaldo Zabelli.

The geophysical characteristics common to several metallic deposits in Maremme of Tuscany are shown by means of schematic cross sections resulting from geophysical studies. These characteristics were applied to determine the extensions of the metallogenetic phenomena.

"Thermoluminescence of Carbonate Rocks as a Radiation Damage Method for Determination of Geologic Age."

The thermoluminescence of the carbonate sediments appears to be the result of damage to the crystal lattice by radiation coming from included radioactive elements. Evidence gathered thus far indicates that thermoluminescence is a function of the age of the crystal lattice and the natural rate of alpha particle radiation. Thermoluminescence can be measured quantitatively by means of a photomultiplier tube. The output of the tube is recorded simultaneously with the temperature of the furnace in which the sample is heated. From this record the amount of thermoluminescence and its distribution into the various electron trapping energy levels in the crystal lattice can be determined. The natural rate of alpha particle bombardment is measured by an alpha scintillation counter. A number of determinations have been made for samples varying in age from pre-Cambrian to Re-

cent. When recrystallization has occurred through faulting, instrusion, or regional metamorphism, the age obtained from these calculations is that of the geologic event which caused the recrystallization. It is hoped that this method may help to provide a more accurate geologic calendar than has been available before.

The study of the above abstracts of the papers presented will show their diverse nature. This variety of papers would be expected to appeal to a general group who are not specialists in the field of geophysics. The papers were well divided among the various geophysical methods, and between applied and theoretical geophysics. However, as with all papers, they present, in the case of case histories, mainly the successful results which are in agreement with the accepted geology of the areas, and not the failures and disagreements which should be submitted as problems for further study in the future.

W. B. Agocs

PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,608,602. G. Muffly. Iss. 8/26/52. App. 8/9/46. Assign. Gulf Research & Development Co.

Detecting Device. An electrical detecting system which may be used for prospecting or well logging and having an a-c field-creating means and separate pick-up means connected to a phase-sensitive discriminator-type rectifier which is sensitized from the a-c supply.

U. S. No. 2,611,004. A. A. Brant and E. A. Gilbert. Iss. 9/16/52. App. 9/15/48. Assign. Geophysical Exploration Co.

Geophysical Exploration. A system of electrical prospecting in which a d-c charging current is periodically passed between two spaced ground points and immediately after interrupting the charging current the potential is observed between two intermediate points, the observed potential being in the same direction as the charging current and due to discharge of the electrical double layer at the surface of conducting bodies in the charging field.

GRAVIMETRIC PROSPECTING

U. S. No. 2,610,507. F. G. Boucher. Iss. 9/16/52. App. 3/13/47. Assign. Standard Oil Development Co.

Gravity Meter. A gravimeter whose range may be extended by adding one or more small riders to the suspended system.

MAGNETIC PROSPECTING

U. S. No. 2,603,687. L. J. Giacoletto. Iss. 7/15/52. App. 9/22/49. Assign. Radio Corp. of America.

Magnetometer. An electron-beam magnetometer in which a-c is applied as the accelerating voltage of a beta-ray spectrometer and the instantaneous voltage measured when the beam traverses the collector aperture by having the collector current trip a thyratron-controlled voltmeter.

U. S. No. 2,605,072. N. E. Klein and W. H. Brattain. Iss. 7/29/52. App. 7/6/44. Assign. U. S. A.

Integral-Drive Magnetometer Head. A self-orienting total-field magnetometer in which the orienting motors are mounted on the magnetometer head so that their position with respect to the magnetic elements remains fixed.

U. S. No. 2,605,341. V. V. Vacquier and J. N. Adkins. Iss. 7/29/52. App. 4/17/44. Assign. U. S.A.

Directional Indicator System. A magnetometric apparatus for indicating on a search airplane the direction to a magnetic peak and having a magnetometer at each wing tip with their respective outputs impressed on four star-connected resistors from which sum and difference voltages are obtained which are amplified and indicated on a c-r tube screen.

U. S. No. 2,605,344. W. H. Brattain, N. E. Klein and M. S. Richardson. Iss. 7/29/52. App. 5/11/44. Assign. U. S. A.

Magnetometer Head. A magnetometer head in which the orienter elements are arranged in pairs and form the sides of a square with their cores forming a continuous magnetic circuit and with the detecting element mounted at its midpoint perpendicular to the plane of the square.

* Gulf Oil Corporation, Patent Department.

U. S. No. 2,606,229. A. W. Brewer and C. A. Jarman. Iss. 8/5/52. App. 10/28/48 and 10/28/49.

Apparatus for the Measurement of Magnetic Fields. A magnetometer for determining the magnitude and direction of the earth's field and having a self-orienting total-field magnetometer, a vertical magnetometer and a magnetometer mounted on a telescope which is automatically kept sighted on the sun; the position and time of day being recorded together with the magnetometer outputs.

U. S. No. 2,610,226. J. M. Klaasse and H. Jensen. Iss. 9/9/52. App. 5/12/50.

Method and Apparatus for Conducting Geophysical Surveys from an Aircraft. An aeromagnetic survey system in which the magnetometer record is correlated with a record of periodic shoran readings together with a signal indicative of the accuracy of the shoran location.

U. S. No. 2,611,802. H. Jensen. Iss. 9/23/52. App. 7/2/46.

Method and Apparatus for Magnetic Exploration. A recording system for aeromagnetic surveying in which the terrain under the aircraft is continuously photographed and the photographic film is periodically edge marked with a number which synchronizes it with the magnetometer record, and additional numbers are stamped on the record to indicate the magnetometer sensitivity and zero setting.

U. S. No. 2,611,803. L. H. Rumbaugh, H. Jensen and J. R. Balsley, Jr. Iss. 9/23/52. App. 7/10/46.

Method and Apparatus for Conducting Geophysical Surveys. A recording system for aeromagnetic surveying in which photographs of the terrain under the aircraft are periodically taken with part of the same film also photographing the magnetometer control dials, radio altimeter reading, and a number which synchronizes the photograph with the magnetometer record.

SEISMIC PROSPECTING

U. S. Re. 23,552 (Original No. 2,544,819). J. J. Babb and N. J. Smith. Iss. 9/30/52. App. 8/29/47 and 3/12/52. Assign. said Babb to Texas Instruments Inc. and said Smith to The California Co.

Apparatus for Marine Seismic Prospecting. A marine seismometer spread having a heavy main cable with branch cables at each seismometer location, the seismometers being mounted on a pivot at the end of its branch cable and with sufficient buoyancy to keep the branch cable vertical but allow the main cable to lie on bottom.

U. S. No. 2,604,954. R. W. Mann. Iss. 7/29/52. App. 1/24/48. Assign. Standard Oil Development Co.

Seismic Exploration Method. A method of reducing impulses caused by the bubble in underwater seismic prospecting by suspending in the water near the explosive a large mass which will distort the bubble from its normally-spherical shape.

U. S. No. 2,604,955. J. E. Hawkins. Iss. 7/29/52. App. 4/18/46. Assign. Seismograph Service Corp.

System for Analyzing Seismographic Records. A system for analyzing seismograms in which the filtering is varied by varying the speed of reproduction and the timing lines are put on the reproduced record by a synchronous motor operating on the timing impulses from the original record.

U. S. No. 2,607,842. A. C. Reid. Iss. 8/19/52. App. 3/2/49. Assign. Stanolind Oil and Gas Co.

Marine Seismometer Spread. A marine seismometer spread which is supported above water bottom by a series of elongated flexible floats having one end attached to the cable and the other end floating horizontally in the water.

U. S. No. 2,609,438. A. C. Winterhalter. Iss. 9/2/52. App. 1/24/47. Assign. Sun Oil Co.

Seismic Exploration Apparatus. A system for seismograph recording by radio in which each detector signal frequency modulates a low-frequency oscillator and this signal modulates a high frequency radio transmitter, the radio signals being separated at the recorder and the detector signals recovered and recorded.

U. S. No. 2,609,885. D. Silverman. Iss. 9/9/52. App. 12/29/50. Assign. Stanolind Oil and Gas Co.

Seismic-Wave Generation. An explosive for seismic prospecting having a continuous distribution of explosive in the form of a vertical helix whose pitch is such that the axial component of detonation velocity is equal to the seismic propagation velocity in the surrounding medium.

U. S. No. 2,610,240. N. Pottorf. Iss. 9/9/52. App. 2/23/49. Assign. Stanolind Oil and Gas Co.

Marine Seismometer Spread. A marine seismometer spread in which the main cable is floated on the surface of the water and the seismometer units have positive buoyancy but are floated beneath the surface by the weight of flexible branch cables.

U. S. No. 2,611,024. J. E. Hawkins. Iss. 9/16/52. App. 9/20/46. Assign. Seismograph Service Corp.

Seismic Signal Amplifying System. A multi-channel seismograph amplifying system in which the plates and screens of the corresponding stage of all channels are fed through individual resistors from a common low-resistance battery, with a separate battery provided for each stage.

U. S. No. 2,612,568. W. B. Hemphill. Iss. 9/30/52. App. 11/7/46. Assign. Socony-Vacuum Oil Co., Inc.

Automatic Gain Control System. An avc system for a seismograph amplifier in which the gain is controlled from the signal level and with the gain control initially having a short tine constant which is gradually increased subsequent to the shot moment as a function of time.

WELL LOGGING

U. S. No. 2,602,331. J. A. Moosman. Iss. 7/8/52. App. 9/22/47. Assign. Johnston Testers, Inc.

Fluid Pressure Recorder. A bottom-hole pressure gauge having a helical Bourdon tube whose free end is connected to a bevel gear which drives a pinion and spur gear, the latter engaging a rack which carries a stylus recording on a clock-driven drum.

U. S. No. 2,602,833. L. M. Swift. Iss. 7/8/52. App. 7/15/48. Assign. Well Surveys, Inc.

Casing Collar Locator. A magnetic casing-collar locator having a central permanent magnet and a high-permeability core magnetically in series between a lower pole piece and a thin annular pole piece and a coil wound on the core, the coil's impedance being measured at the surface and being low when the casing completes the magnetic circuit causing saturation of the core and high when the casing gap reduces the flux through the core.

U. S. No. 2,604,181. R. B. Basham and C. W. Macune. Iss. 7/22/52. App. 8/25/48. Assign. Westronics, Inc.

Apparatus for Locating Binding Areas Around Well Casing. A device for locating points where pipe is stuck and having an electrically-driven vibrator elastically suspended below a vibration pick up whose output is recorded at the surface, both the vibrator and pick up having radial arms which engage the pipe.

U. S. No. 2,604,526. R. B. Basham and C. W. Macune. Iss. 7/22/52. App. 1/14/50. Assign. Westronics, Inc.

Line Measuring Device with Correcting Mechanism. A sheave-type line-measuring device in which sheave revolutions are counted by a selsyn system and in which known corrections for sheave diameter are made by interposing an intermediate selsyn on a differential gear on one side of which the correction is introduced.

U. S. No. 2,605,321. J. E. Owen. Iss. 7/29/52. App. 6/21/51. Assign. Geophysical Research Corp.

Electrical Well Logging Apparatus. A system for simultaneously obtaining an S-P log with an a-c resistivity log using guard electrodes which are made up of a series of insulated short sections coupled to the energizing cable through condensers so that the guard electrodes do not short circuit the spontaneous potential of the formations.

U. S. No. 2,605,637. E. D. Rhoades. Iss. 8/5/52. App. 7/28/49. Assign. U. S. A.

Surveying of Subsurface Water Tables. A method of testing fluid at various levels of a borehole by inserting a series of packers with separate strings of non-concentric tubing reaching to the several levels and through which soundings may be made.

U. S. No. 2,607,220. P. W. Martin. Iss. 8/19/52. App. 4/14/47.

Means for Measuring Conditions in Deep Wells. An electrical system for simultaneously measuring both pressure and temperature in a well in which the pressure element varies an inductor in a resonant circuit in the well and the temperature element varies an inductor in a resonant circuit in a different frequency band, a-c being supplied from the surface and the current in each band indicated.

U. S. No. 2,607, 221. E. C. Babson, R. R. Ormsby and M. C. Turner. Iss. 8/19/52. App. 5/18/46. Assign. Union Oil Co. of California.

Flowmeter. A subsurface flowmeter having a flow-driven propeller which carries a permanent magnet and actuates a magnetic switch to control an electromagnetic-wave signal or an acoustic signal which is picked up at the surface.

MISCELLANEOUS

U. S. No. 2,604,704. W. R. Woodward. Iss. 7/29/52. App. 11/24/43. Assign. U. S. A.

Hyperbolic Position-Plotting Instrument. Apparatus for plotting position from the time difference of synchronized signals from two pairs of radio stations and having cords passing through the station locations on a map and connected at the point to be plotted where they are also kept taut, the cords being paid out at rates differing by the time difference observed.

U. S. No. 2,604,779. W. R. Purcell. Iss. 7/29/52. App. 5/11/48. Assign. Shell Development Co.

Method and Apparatus for Measuring Capillary Pressure. A method of obtaining the mercury capillary pressure curve for drill cuttings in which the cuttings are placed in a cell and evacuated, and the volume of mercury displaced by the cuttings observed at various values of pressure as gas is admitted to the cell.

U. S. No. 2,607,996. R. D. Moyer. Iss. 8/26/52. App. 10/23/45.

Apparatus for Measuring, Indicating, and Recording True Vertical and Horizontal Distances. A surveying vehicle in which a pendulum controls friction-cone drives to move a stylus which records the horizontal and vertical components of distances traversed by the vehicle.

U. S. No. 2,612,036. F. A. Angona. Iss. 9/30/52. App. 11/1/47. Assign. Socony-Vacuum Oil Co., Inc.

Apparatus for Measuring Interstitial Water Content of Well Cores. A semi-permeable membrane for use in measuring the interstitial water content of cores which consists of a layer of powdered talc sandwiched between two discs of unglazed porcelain.

SELECTED LIST OF U. S. PATENTS ISSUED DURING THE THIRD QUARTER OF 1952

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2,607,228	288
2,607,230	16
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2,607,417	48
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2,607,828	188, 132
2,607,830	188, 132
2,607,842[a]	360
2,607,858	484
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[a] Abstracted on preceding pages of this issue.

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REVIEWS

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Prospection Géophysique, by Edmond and J. P. Rothé, Vol. II, Gauthiers Villars, Paris, 1952.

This volume is the second and final installment of a treatise on geophysical prospecting by J. P. Rothé and his father Edmond, now deceased. Volume I was published in 1950, and a comprehensive review of it was made by Frank Press in the January 1951 issue of *Geophysics*, pages 160–1, to which the reader will decidedly wish to refer.

It should be pointed out here that in 1930 Raymond Rothé published his *Les méthodes de Prospection du sous-sol*, and in 1943 *Questions actuelles de Géophysique*. These earlier books discuss very interestingly certain aspects of the geophysics of the earth; they also contrain mathematical treatment of numerous problems of applied geophysics, not repeated in the two following books. Indeed, the four volumes are separate parts of the same subject and should be read together. They constitute a valuable and substantial contribution of more than 1900 pages to the present geophysical literature.

Volume I dealt with seismic methods and radioactive methods by ionization techniques. Volume II picks up where its predecessor left off, and deals with the balance of the processes of the geophysical workshop: gravimetric, magnetic, electrical, and geothermal methods. As was the case previously, each method is presented in two chapters, one concerning the theory, technical aspects, and apparatus; the other dealing with practical examples of field work. An operning statement at the beginning of the chapters concerning the gravimetric and magnetic methods specificially brings to the attention of the reader the fact that part of the subject matter will be found in *Les méthodes de Prospection du sous-sol*.

Gravimetric methods are discussed in two chapters covering 178 pages. The discussion of the

modern instruments now in use is quite adequate. The chapter on actual cases of field work is varied and very interesting.

Electrical methods are expounded in 200 pages. This is by far the most interesting part of the book. For one thing, the physical and mathematical treatment is clear and thorough. It covers adequately the potential and induction methods, as well as the technique by telluric currents and the natural phenomenon of spontaneous polarization. Very well worth reading is a subchapter on the skin effect and on the similitude in geophysics. However, the examples of field work are still much more intresting. They are numerous and varied, and illustrate well the flexibility and resolving power of the electrical methods. The fact is that this phase of geophysical prospecting, particularly under the impulse given it by C. and M. Schlumberger and their co-workers, has extended its field of application and reached a development in the Eastern Hemisphere of which many geophysicists are hardly aware in this country. In this respect, this section of the book makes good reading, indeed.

As a companion to the surface electrical methods, there is a chapter on electrical logging. This technique of investigation in drill holes is undergoing constant progress, almost daily. The chapter, although well written, does not give a full picture of the present-day tenchiques and possibilities, the more so in that electrical logging, now, is becoming more and more a segment of petroleum technology and is better treated in that light.

Magnetic methods occupy 168 pages. The theoretical presentation is excellent and the practical example of field work very ably discussed. The short subchapter on the airborne magnetometer, even though going only into the essentials, is quite comprehensive.

The last part of the volume deals with geothermic methods. The physical and geological generalities of this section are excellent. They are rounded up by a few examples of field work which are interesting.

As was pointed out in the review of the first volume, *Prospection Géophysique* is a work of the textbook type. The theoretical and physical developments are presented in a lucid and clear manner; this does not happen by chance, and has much to do with the professional leanings of E. and J. P. Rothé. As to the practical part of the book, there is no question but that it constitutes a very valuable and substantial contribution to the present literature on applied geophysics on account of the number and variety of the examples discussed.

A very complete bibliography accompanies each section of the book and should prove very useful to the reader. There is no name nor subject index.

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Theoretical Petrology, First Edition, by Tom F. W. Barth, John Wiley and Sons, Inc., New York 1952, 387 pp., $6.50.

Modern petrology has evolved from empirical deductions based upon field relationships extended by optical and chemical determinations to become "physico-chemistry applied to the crust of the earth."[1] Never losing sight of this concept, Professor Barth brings together the widely-scattered experimental data of geophysical and geochemical laboratories, reconciles them with geological field observations, and then presents the most recent and best interpretations, in his opinion, of the rock-forming processes. The trend toward quantitative and mathematical geology has gained a contribution.

Geophysicists and geologists, who are concerned with the problems of oil exploration, may be inclined to overlook this volume feeling that it neglects sedimentary rocks (only twenty-three pages being devoted to their formation). It should be recognized, in this connection, that a tendency exists for petrologists to emphasize the mineralogically more appealing igneous and metamorphic rocks.

[1] Tom F. W. Barth, *Theoretical Petrology*, (1952), p. v.

This book, which in no sense is elementary, was written primarily, though not exclusively, for petrologists. It certainly recognizes their preference for igneous and metamorphic petrology. Furthermore, the author's field and laboratory experience has dealt fundamentally with igneous and metamorphic problems.[2]

Professor Barth introduces his *Theoretical Petrology* with a short discussion of the physics and chemistry of the earth. Part I, which is of interest to all earth scientists, treats with the earth's origin, its heat distribution, its strength, its concentric structure and the composition of the lithospheree. A concluding section on geochemical cycles reveals the author's inclination toward anatexis or transformation of sediments into mobile igneous material by deep geosynclinal burial.

Instead of the customary practice of dealing with the primary igneous rocks at the outset, sedimentary rocks and their formation are the subjects of Part II, where only the most fundamental aspects are treated. Differentiation, which is usually considered to be only a problem of igneous petrology, is cleverly applied, in another sense, to the common sedimentary oxides. Ordinary mechanical and chemical processes bring about an orderly separation of sedimentary oxides and of the resulting sedimentary rocks on the following basis of increasing solubility; (1) silica (quartz sand), (2) sesquioxides (clay, bauxite, and iron hydrates), (3) lime and magnesia (limestone and dolomite), (4) alkalies and their respective products (alkali salts).

Part III, "Igneous Rocks," the major division of the book, is subdivided into four principal sections: (1) Descriptive Classifications, (2) Physical Chemistry of the Minerals, (3) Magmas and their Locales, (4) Rocks as Products of Defined Processes. A word of caution introduces the discussion of igneous rocks. Although lavas must be regarded as igneous (having congealed from a magma) immediately on recognition, this descriptive term should be restricted in its application to deep-seated crystallines until positive proof of their actual magmatic nature has been obtained. Bowen and Tuttle[3] doubt the existence of peridotite magmas and others of more extreme opinions claim that magmatic granites do not occur. Mineralogical classifications and chemical compositions are discussed briefly to prepare for examples of petrochemical calculations and classifications that follow. The physical chemistry of the igneous rock-forming mineral families is developed by continual reference to equilibrium diagrams. One attractive feature of this volume is its presentation of so many of these schematic diagrams in a single reference. To gain an understanding of magmas, Professor Barth discusses the constitution of silicate melts, silicate-water systems, vapor phase, viscosity, and temperature of magmas and magma tectonics. Magmatic differentiation, rock series and their distributions, and granitization conclude the petrology of igneous rocks.

Metamorphic rocks remain the least understood of the three principal classes, but Part IV offers a coherent résumé which is introduced by a description of the typical metamorphic minerals. Thermodynamic principles, which apply in the study of metamorphism, are discussed. A special section, which is devoted to contact metamorphism before entering upon the more difficult problems of regional metamorphism, is appropriately followed by consideration of the formation of the contact silicates and their related gaseous phases. Structure of metamorphic rocks, recrystallization, metamorphic diffusion, metamorphic differentiation, mineral facies of regional metamorphism, special mineral facies, regional metamorphism, and a brief mention of migmatites complete the last division of this book.

Petroleum geologists are having their attention increasingly directed toward crystalline rocks as deep drilling encounters intrusive masses within the sedimentary section as well as the intrusive and metamorphic rocks comprising the crystalline basement. Regional aeromagnetic surveys are defining sub-sedimentary trends which arise, principally, from magnetization contrasts between crystalline rock types. Geophysicists are applying with ingenuity their oil-finding methods in the exploration for buried metallic mineral deposits, most of which are associated with the igneous and metamorphic rocks that are so well covered by this modern treatise. All geophysicists and geologists, whatever their

[2] N. L. Bowen, *Science*, Vol. 115 (April 18, 1952), p. 444.

[3] N. L. Bowen and O. F. Tuttle, *The System MgO-SiO_2-H_2O, Geol. Soc. of Am. Bull.*, Vol. 60, No. 3 (March 1949), 454–460.

momentary interests might be, will find in Professor Barth's new book a modern presentation of petrology. Professor Krumbein, in his review of this book,[4] believes that "many principles of petrology developed in connection with igneous and metamorphic rocks . . . can be adapted to sediments, and the careful reader may well acquire new ideas for his own field of application." The long-standing and artificial distinction between "soft" and "hard" rocks must inevitably disappear as geologists anad geophysicists realize that "igneous and sedimentary rocks grade into each other on the surface of the earth . . . and . . . in the depth of the earth. The continuity is complete; the cycle in inorganic nature is without a break." (Sederholm, 1907.)[5]

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Geology, by O. D. von Engeln and Kenneth E. Caster, McGraw-Hill Book Company, Inc., New York, 1952, 730 pp., $7.00.

A significant and recent addition to the group of textbooks for courses in elementary geology is the one written by O. D. von Engeln, of Cornell University, and Kenneth E. Caster, of the University of Cincinnati. This volume of 730 pages is published by the McGraw-Hill Book Company, Inc., at a list price of $7.00. Typography, binding, paper, and format are attractive and of the highest quality. The authors are too well known in their respective fields to require personal introduction in a book review.

This text presents geology in such an attractive manner that it undoubtedly will lead many of the better students into the various branches of earth sicence. The vast majority of students taking elementary courses in geology will not become professional geologists, hence it is of great importance that a text be of such quality as to be of cultural significance to these students and not produce a dislike for the subject. The style of presentation and content of the chapters of this new text have been developed to appeal to the student taking geology as a cultural course and at the same time to meet the requirements of the student who will ultimately become a geology major and professional geologist.

The Preface, explaining the objectives of the authors and the method of presentation of the material, is followed by four major sections: "Introduction to Geology"; "The Natural History of Igneous Rocks"; "Structure, Process, Forms"; and "Geologic History." These sections are divided into appropriate chapters, each of which is closed with a list of selected references that serve as guides to supplemental reading by the inquisitive student. Significant questions that introduce a spirit of logical thinking and deduction are included in each chapter.

Controversial matters are acknowledged as such and several points of view and opinions are presented; there is no dogmatism expressed on these subjects. The first use of a technical term is called to the attention of the student by boldface type and is accompanied by a definition or explanation at that point.

The numerous illustrations have been carefully chosen for maximum value and are clear and sharp in detail; diagrams and charts are well executed and will be intelligible to the beginning student. The majority of the photographs are refreshingly new, but some classical views have been included where important. Explanations and descriptions under the figures are complete and expressive.

The second half of the book presents geologic history, beginning with the Pleistocene Glacial Epoch and working back to the pre-Cambrian. The chapter on the pre-Cambrian is followed by one on the interior of the earth; the book is closed with a chapter on the age and origin of the earth.

This reviewer has the highest praise for the von Engeln and Caster textbook, but does question the feasibility or desirability of teaching geologic history in reverse order of the occurrence of events.

[4] W. C. Krumbein, *Bull. of A.A.P.G.*, Vol. 36, No. 8 (August 1952), p. 1649.
[5] Tom F. W. Barth, *Theoretical Petrology*, (1952), p. 369.

It is recognized that there may be some argument for teaching from the known "to the unknown," but it is believed that this slight advantage is greatly outweighed by the difficulty and illogicalness of presenting a sequence of physical events and the evolutionary development of life in the *reverse* order from which the events actually happened or life evolved. It is believed that the student can comprehend more readily the relationships between causes and effects if they are discussed in the direct order of their occurrence. However, it must be acknowledged that the authors have made a most effective demonstration of the method of presenting geologic history from the present toward the remote past.

The book is recommended as a text for a course in elementary physical and historical geology.

MARCELLUS H. STOW
Washington and Lee University
Lexington, Virginia

Geodesy, by G. Bomford, Oxford University Press, New York, 1952, 451 pp., $10.00.

The primary purpose of this book is to record current methods of geodetic observations and reductions. However, several chapters are devoted to discussions of subjects pertinent to the geophysical prospecting profession, thereby enabling the reviewer to discuss this book, in spite of the fact that he is no geodesist. Included in the geodetic portion is a chapter which has particular application to off-shore surveying in that factors involved in the anomalous propagation of radar waves are discussed in some detail, including means of detecting and correcting this phenomenon. In addition, chapters are presented dealing with conventional geodetic subjects, such as field work and computational aspects of triangulation surveys, geodetic astronomy, and means for determining heights above sea level.

One of the two chapters of particular interest to geophysicists includes a discussion of several types of geophysical surveys, such as gravity, magnetic, and seismic; the other deals with such topics as the figure of the earth and crustal structure. Considerable emphasis is given to a description of various types of pendulums, including those used for observations of gravity at sea. A separate section entitled, "Other Gravimetric Instruments," describes briefly various types of gravity meters used in geophysical prospecting, including the Hartley, Gulf, Worden, Frost, Ising, and Norgaard types. In addition, the Haalck gas pressure type used a number of years ago in marine work is mentioned, as well as the Lejay inverted pendulum. Another more recent instrument, developed by Gilbert, described as a vibration gravity meter, and used susccessfully at sea in 1948, is discussed in some detail. The results obtained with this meter when compared with pendulum data are stated to be accurate to within plus or minus 1½ milligals. The discussion in the section on magnetic surveys is confined primarily to a brief description of the conventional magnetic recording instruments used in observatories. This chapter concludes with what can be described at best as a cursory discussion of the principles of reflection and refraction seismic prospecting.

The chapter devoted to the figure of the earth and crustal structure contains a number of interesting sections dealing with a concise presentation of formulae for the computation of gravitational potential and attraction, the different systems for the reduction and use of gravity observations, as well as deviations of the vertical. In spite of the thoroughness with which these aspects of gravity computations and reductions are discussed, no mention is made of the problems involved, nor the need for, earth tide corrections on gravity observations made with those gravity meters which are sufficiently sensitive to respond to changes in gravity caused by earth tides.

The concluding sections include a discussion of problems involved in density anomalies and the strength of the earth's crust, with emphasis on stress differences caused by unequal loads, the interrelationships of temperature and strengths, and the location of isostatic mass anomalies. An interesting presentation of earth movements from the geodesist's viewpoint is included in the section on earth movements.

The volume concludes with a series of seven appendices, and a comprehensive bibliography of

more than 300 items taken from the literature of geodesy, seismology, tectonophysics, and geophysical prospecting, with emphasis on European publications. Included in these seven appendices are several which should find ready application in the routine, as well as the research duties and problems of exploration geophysicists. They include gravity reduction tables based on the work of Hayford, as well as Cassinis; spherical harmonics, the theory of errors, and the density and refractive index of damp air which has application in various types of surveying methods. Special attention is given in the appendix to the theory of errors, to the different types of error, the definition and computation of probable error, and least squares. This volume should prove valuable to those exploration and research geophysicists dealing with problems arising in gravity surveys and their interpretation, as well as problems involving the strength of the earth's crust.

RICHARD A. GEYER

Spindletop, by James A. Clark and Michel T. Halbouty, Random House, New York, 1952, 306 pp.

Spindletop is a fast-moving historical account of the petroleum production of one salt dome, Spindletop, near the town of Beaumont, Texas. The impact of the Lucas gusher was felt outside of Beaumont, even to the limits of our globe. The most important impact was on the organization of the petroleum industry for it was here that several of the present large major oil companies were founded. The second impact was upon the geological profession. Spindletop was discovered by Pattillo Higgins who was not a geologist by the standards of his day but who had to persevere against the almost unanimous condemnations of Spindletop by the recognized professional geologists of industry and government. Spindletop's success thereby gave birth to Gulf Coast geology.

The team of authors embodies journalistic and geologic ability and experience. Clark is a petroleum editor for one of Houston's leading newspapers. Halbouty is a practicing geologic consultant in the same city. The combination produces in *Spindletop* a very readable account of authenticated material.

The book is of interest to anyone engaged in petroleum exploration because it presents, in very entertaining fashion, the background of many of the practices of leasing, drilling, and financing in which we are engaged today. Geophysics does not enter into the exploitation of Spindletop at any point in the account. Moreover, the only technical material in the book is a short appendix by Halbouty which is confined to a general treatment of the salt dome phenomenon. The book is, nevertheless, rewarding to any geophysicist who wishes to obtain a more comprehensive perspective of his industry.

NELSON C. STEENLAND

Handbook of Engineering Fundamentals, Second Edition, by O. W. Eshbach, John Wiley and Sons, Inc., New York, Chapman and Hall, London, 1952, $10.00.

John Wiley has again published Eshbach's classic handbook. The first edition, published in 1936, was, as stated in the preface, a "departure from traditional publication" of such material because it included the "basic facts and principles" of technology and engineering.

The second edition very commendably brings to date these basic facts and principles, together with the routine revision of the tabular material. The entire volume has become, in reality, a very comprehensive and up-to-date textbook of general physics although, of course, in abridged form. The *Handbook* is ideally suited for use in geophysical research laboratories.

NELSON C. STEENLAND

The Dispersion of Surface Waves on Multi-layered Media, by Norman A. Haskell, *Geophysical Research Papers*, No. 9, Air Force Cambridge Research Center, Cambridge, Massachusetts, Aug. 1951, 28 pp.

One of the most powerful techniques that seismologists use to deduce the structure of the earth's

superficial layers is to observe the dispersion of surface waves, such as Love waves or Rayleigh waves, from earthquakes and to compare this with theoretical curves computed for various assumed configurations of near-surface layering. The calculation of such curves is a rather tedious process and it has not been practical, in the past, to compute Rayleigh wave dispersion cuvres for more than two layers. Love wave dispersion curves, intrinsically simpler, have been computed for as many as three layers.

Dr. Haskell's paper develops techniques for extending the number of layers that can be conveniently handled in dispersion calculations. These techniques make use of a matrix formalism developed by W. T. Thomson,[1] which Haskell has applied to several types of surface waves, such as Rayleigh waves, Love waves, Stoneley waves, and waves in a fluid layer.

The author has calculated Rayleigh wave dispersion curves by use of this procedure for one 2-layer and two 3-layer configurations, representing the possible structure of the earth's crust and its substratum beneath the continents. The three curves are compared with data on Rayleigh wave group velocities observed at various frequencies from earthquakes. The scatter of the observed points is greater than the separation of the curves so that it is not possible to establish or disprove any of the assumed models by this method.

The general solution developed for waves in which all particle motion is in the vertical plane and in which amplitude diminishes exponentially with depth shows the particle motion for all waves of this type must be along an ellipse with axes respectively vertical and horizontal. For Rayleigh waves in a homogeneous medium, this ellipse is retrograde; for other surface waves it can be direct.

For a dissipative medium, it is shown that the axes of the ellipse can be inclined from the vertical. Imperfect elasticity is thus suggested as the cause of the inclination often observed in Rayleigh waves from shothole explosions.

Dr. Haskell's paper is a valuable contribution and should be most useful to earthquake seismologists as well as to those who desire a better understanding of the ground roll encountered in seismic prospecting.

MILTON B. DOBRIN

"Electrical Noise from Instrument Cables Subjected to Shock and Vibration," by Thomas A. Perls, *Journal of Applied Physics*, Vol. 23, 1952, pp. 674–680.

This paper should be of interest and of possible value to all who make use of piezoelectric gauges in geophysical research or operations. Such gauges have had widespread use in fundamental studies of seismic signals and in certain newly introduced logging techniques as well as in wartime and postwar research on underwater explosions. A serious limitation upon the performance of all crystal type gauges, and particularly the recently introduced barium titanite transducers, is in the electrical noise that is generated when the cable between gauge and preamplifier is subjected to shock or vibration. In the present paper Mr. Perls discusses the nature of such noise and suggests a technique for reducing this spurious disturbance.

Theoretical analysis as well as experiments with several types of concentric cables indicated that flexing or distorting a cable causes a separation over a small area of the conductor and the dielectric. If such a gap is suddenly introduced, high potentials can be developed in the air capacitor so created. Some standard cables were observed to develop as much as 500 millivolts across the terminals as a result of severe manual distortion.

Although special "low noise" cable is commercially available, its large diameter and high rigidity make it unsuitable for many applications requiring very small gauges. A new type of low-noise cable is proposed in which concentric layers of conducting rubber are vulcanized to the outside and inside of the dielectric. Instructions are given for making short lengths of such cable in the laboratory.

MILTON B. DOBRIN

[1] W. T. Thomson, "Transmission of Elastic Waves through a Stratified Solid Medium," *Journal of Applied Physics*, Vol. 21 (1950), pp. 89–93.

"Radioactivity of Waters Issuing from Sedimentary Rocks," by Stanko Miholić, *Economic Geology*, Vol. 47, No. 5, August 1952.

During recent years, considerable data concerning gamma radiation intensities in sedimentary rocks has been available to me. This data has come chiefly from the Gulf Coastal Plains of the United States and from gamma radiation logs of oil wells drilled through these geological formations.

In the Cretaceous strata it has been found that limestones, in general, have about 1½ to 2 micro-roentgens per hour of gamma radiation, while the shales of same age will vary from 8 to 16 micro-roentgens per hour. In general, the darker shales will have the greater intensity of radiation. These findings apparently are in agreement with Mr. Miholić's disclosures, although there would be some disagreement in the theory of origin of this radioactive matter.

In the formations of Eocene Age, and more particularly the Frio Section in South Texas, unusual intensities of gamma radiation are frequently encountered ranging up to 30 and 40 micro-roentgens per hour. The origin of these highly radioactive sediments has been traced to varying amounts of volcanic ash (which is naturally radioactive) having settled over this area during the period of deposition. These ash beds are contained mostly within the sandstones but are occasionally found in shales.

The radioactive content of waters that are produced from oil wells has been of considerable interest. It has been determined that in wells producing large amounts of salt water, a highly radioactive deposit accumulates around the immediate point of entry. The strength of this radiation seems to be directly proportional to the amount of salt water produced—the greater the amount of water, the greater the intensity of radiation. Large sample quantities of this salt water have been checked for gamma radiation but the percent of radioactive materials per unit volume of water was too low to be measured with field equipment. This fact has led to the theory that a precipitation from the salt water, possibly potassium (radioactive), is deposited at the point of entry into the well, probably from pressure or temperature differentials at that point. This deposition eventually reaches sufficient radiation strength to overshadow the normal intensities of gamma radiations encountered within the formations.

J. H. Russell
Perforating Guns Atlas Corporation
Houston, Texas

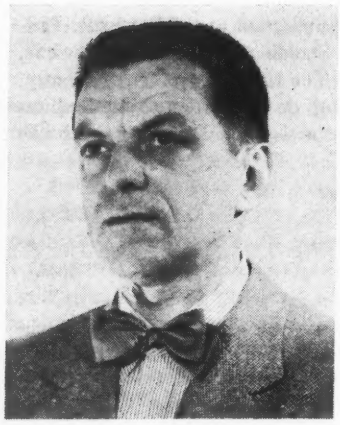
PUBLICATIONS RECEIVED

Listed below are publications received by the society since publication of the last issue. Periodicals indicated by the asterisk (*) have been forwarded to the Standing Committee on Reviews, and will be placed in the permanent depository of the society at The University of Tulsa Library. These publications are available for loan to members of the society on application to the business manager. Other publications are held for a short time at the business office. Disposition of books listed is by direction of the Standing Committee on Reviews.

Periodicals

American Journal of Science, Vol. 250, Nos. 9 & 11 (Sept. & Nov., 1952)
**Annales de Geophysique*, Vol. 8, No. 2 (1952)
**Beihefte zum Geologischen Jahrbuch*, Nos. 3, 4 & 5 (1951, 1952 & 1953)
**Boletin de la Asociacion Mexicana de Geologos Petroleros*, Vol. 4, Nos. 1–2 & 3–4 (Jan.–Feb. & March–April, 1952)
**Bollettino de Geodesia*, Vol. 11, No. 1 (Jan.–March, 1952)
**Bulletin of the Earthquake Research Institute, Tokyo*, Vol. 30, Nos. 2 & 3 (June & Sept., 1952)
**Bulletin Geodesique*, Nos. 23 & 24 (March & June, 1952)
**Bulletin of the Seismological Society of America*, Vol. 42, No. 3 (July, 1952)
**Comptes Rendus du Comite National Francais de Geodesie et Geophysique*, No. 950
**Deutsche Geodetische Kommission*, Vol. 24–26, No. 3 (1952)
**Deutsche Hydrographische Zeitschrift*, Vol. 5, Nos. 1–3
**Economic Geology*, Vol. 47, Nos. 4 & 6 (June–July & Sept.–Oct., 1952)
**Erdöl und Kohle*, Vol. 5, Nos. 7, 8 & 9 (July, Aug. & Sept., 1952)
**Geofisica Pura e Applicata*, Vol. 22, Nos. 3–4 (1952)
**Geoloski Vjesnik*, Vols. 2, 3 & 4 (1948–1950)
**Geophysical Exploration*, Vol. 5, No. 2 (1952)
**Geophysical Notes, Tokyo University*, Vol. 5, No. 1 (1952)
**Gerlands Beiträge zur Geophysik*, Vol. 62, No. 4 (1952)
Journal of Applied Physics, Vol. 23, Nos. 7, 8 & 10 (July, Aug. & Oct., 1952)
**Journal of Geophysical Research*, Vol. 57, No. 3 (Sept., 1952)
Journal of the Institute of Petroleum, Vol. 38, Nos. 342, 343 & 344 (June, July & Aug., 1952)
**Meteoros*, Vol. 2, Nos. 1–2 (Jan.–June, 1952)
**Mitteilungen aus dem Institut für Geophysik*, Nos. 18–19 & 20–21 (June, Oct. & Dec.. 1951; Jan., 1952)
**Nafta*, Vol. 8, Nos. 6 & 7–8–9 (June & Jul.–Aug.–Sept., 1952)
**Proceedings of the Cambridge Philosophical Soeity*, Vol. 48, No. 4 (1952)
**Quarterly Journal of the Geological Society of London*, Vol. 107, No. 427 (Aug. 29, 1952)
Review of Scientific Instruments, Vol. 23, Nos. 7, 9 & 10 (Jul., Sept. & Oct., 1952)
**Rocznik*, Vol. 21, Nos. 1 & 2 (1951)
**Science*, Vol. 116, Nos. 3003–3020 (Jul. 18–Nov. 14, 1952)
**Science Reports of the Tohoku University*, Vol. 4, No. 1 (June, 1952)
**Scientific Monthly*, Vol. 75, Nos. 2, 3 & 4 (Aug., Sept. & Oct., 1952)
**Tellus*, Vol. 4, No. 2 (May, 1952)

CONTRIBUTORS



PIERRE M. HONNELL

PIERRE M. HONNELL received his B.Sc. in electrical engineering in 1930 and E.E. degree in 1938 from the A. and M. College of Texas. He pursued graduate studies at the Technischen Hochschule in Vienna 1933–1934; at the Massachusetts Institute of Technology (M.Sc. in E.E. 1939); the California Institute of Technology (M.Sc. in 1940); and at Saint Louis University (Ph.D. in Geophysics 1950).

He was a member of the Technical Staff of Bell Telephone Laboratories, 1930–1933; and in the Geophysical Division of The Texas Company, 1934–1938.

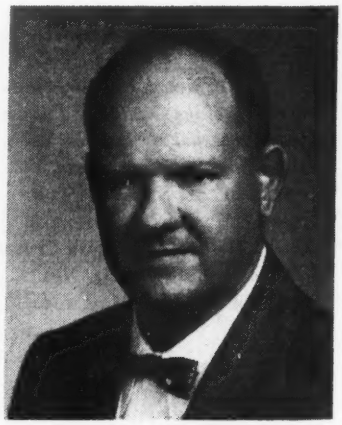
Called to active duty in 1941 from the Officers' Reserve Corps, he reported as a First Lieutenant to the Signal Corps School, Fort Monmouth, New Jersey. A year later he was assigned to the Department of Chemistry and Electricity, United States Military Academy, West Point, New York, rising to the grade of Lieutenant Colonel. In addition to his teaching and administrative duties, he designed and supervised the installation of the Electronics Laboratory at the Academy.

Professor Honnell has taught at Southern Methodist University, and the University of Illinois. He is presently Professor of Electrical Engineering at Washington University, St. Louis, Missouri.

Now a Colonel in the Signal Corps, USAR, he was awarded the Legion of Merit Medal in 1946 for his services at West Point. Dr. Honnell is a member of the Society of Exploration Geophysicists, Seismological Society of America, American Geophysical Union, American Institute of Electrical Engineers, Institute of Radio Engineers, Tensor Club of Great Britain, American Association for the Advancement of Science, Tau Beta Pi, and Sigma Xi.

C. W. HORTON received his B.A. degree in 1935 and his M.A. degree in 1936 from The Rice Institute. Except for one year (1937–1938) in the Graduate College of Princeton University, he worked for Shell Oil Co. from 1936 to 1943. From 1943 to 1945 he was a Research Associate at the Underwater Sound Laboratory at Harvard University. From 1945 to the present he has been a Research Physicist at Defense Research Laboratory, The University of Texas. He received his Ph.D. degree in Physics from The University of Texas in 1948. Since 1946 Dr. Horton has been a member of the faculty of The University of Texas and now holds the rank of Associate Professor.

Dr. Horton is a member of The Society of Exploration Geophysicists, The American Physical Society, American Association of Petroleum Geologists, Seismological Society of America, American Geophysical Union, and Sigma Xi.



C. W. HORTON

LYNN G. HOWELL received the degrees of Bachelor of Arts and Master of Arts from the University of Texas in 1925 and 1926. He received his Doctor of Philosophy in physics from the California Institute of Technology in 1930.

Since 1930 he has been engaged in geophysical research with the Humble Oil & Refining Company.

From 1941 to 1945, he was on leave from the Humble Company with the Section T group at the Department of Terrestrial Magnetism and the Applied Physics Laboratory of Johns Hopkins University in and near Washington, D. C.

He is a member of the American Physical Society, the American Geophysical Union, the Society of Exploration Geophysicists, the Seismological Society of America, Sigma Xi, and the Houston Geological Society.

LYNN G. HOWELL

ARLAND I. INNES

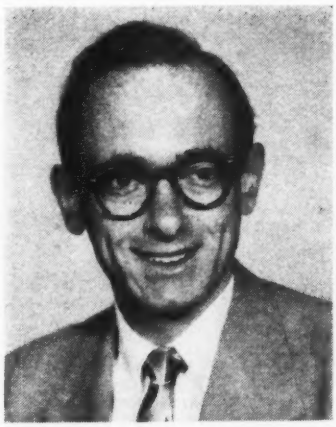
ARLAND I. INNES received his B.S. in Mathematics in 1925 from the University of Toledo. During 1925–1927, he had a teaching fellowship at Haverford College, Haverford, Pennsylvania, where he received an M.A. in Physics in 1927. He was employed by the Geophysical Research Corporation as a chief observer on a refraction crew in June 1927. He was promoted to party chief in November 1928 and to supervisor in 1942. He is currently supervising seismic work for Amerada Petroleum Corporation in West Texas and southeastern New Mexico. He is a charter member of S.E.G. and the Tulsa Geophysical Society, and a member of A.A.P.G.

JOHN R. KILLOUGH

JOHN R. KILLOUGH, a native of the western United States received his B.S. degree in Forestry and Range Management from Utah State College. He has for the past eleven years been employed by various agencies of the U. S. Department of the Interior including the Indian Service, National Park Service, General Land Office and the Bureau of Land Management in land and resource management work. He spent three years with the U. S. Army Engineers Topographic Mapping Battalion in Africa and the Pacific. He has engaged in the development of methods and techniques for reseeding range lands by airplane, utilization of runoff waters to increase forage production, the control of poisonous plants and the eradication of harvester ants and other resource depleting insects. In his work for the various land administration agencies of the government he has assisted in compiling resource inventories in several western states, and participated in programs for the management, disposal and protection of the public resources. He is the author of articles published by the Journal of Forestry, Journal of Range Management and other trade journals and periodicals. He is at present amployed by the Bureau of Land Management in the capacity of Area Manager for the Big Horn Basin of Wyoming and Montana.

CARL KISSLINGER, born in St. Louis, Mo., in 1926, received his B.S. degree in geophysics in 1947 from St. Louis University. Previously he had served as a radio technician in the U. S. Navy from 1944 to 1946, instructing in radar at Treasure Island, California. He held the Shell Fellowship in Geophysics at St. Louis University from 1947 to 1949, and in this time completed work for the M.S. degree. Following a brief period of employment by the Shell Oil Company, he joined the faculty of the Department of Geophysics and Geophysical Engineering of St. Louis University as an instructor, a position he holds at present. In June, 1952, he received the Ph.D. degree, with a major in geophysics and a minor in mathematics.

He holds memberships in the Society of Exploration Geophysicists, the American Geophysical Union, the Seismological Society of America, the St. Louis Academy of Science, and Sigma Xi.



CARL KISSLINGER

E. F. NEUENSCHWANDER was born on September 14, 1909 in Baylor County, Texas.

He attended the University of Texas and received the Bachelor of Science Degree in Electrical Engineering in 1932. He spent the years of 1932–34 doing post graduate work in radio and electrical engineering at the University of Texas.

Mr. Neuenschwander was employed by the Humble Oil & Refining Company in 1934 in the Geophysics Exploration Department for seismic field work. He transferred to the Geophysics Research Department of the Humble Company in 1937. During the war, he was engaged in defense work in connection with an explosives program under the direction of the Office of Scientific Research & Development.

He is a member of Tau Beta Pi, Eta Kappa Nu, the Society of Exploration Geophysicists (Houston Section), American Radio Relay League, and the Institute of Radio Engineers.

E. F. NEUENSCHWANDER

ANDREW L. PIERSON III

ANDREW L. PIERSON III was born in Galveston, Texas on January 29, 1917. Initial engineering training was received at The Rice Institute and the University of Houston. During the war Air Force electronics training in communications was received at Scott Field, Illinois; radar training was obtained from Army Electronics Training Center (Harvard and M. I. T.) in Cambridge, Mass. and the Air Force Radar School, Boca Raton Field, Florida. Field experience was obtained doing airborne radar development and maintenance work with the Eighth Air Force in England; the rank of captain was attained. After the war, at the University of Texas the Bachelor of Science Degree in Electrical Engineering was received in June 1948 and the Master of Science Degree in Electrical Engineering was received in June 1949.

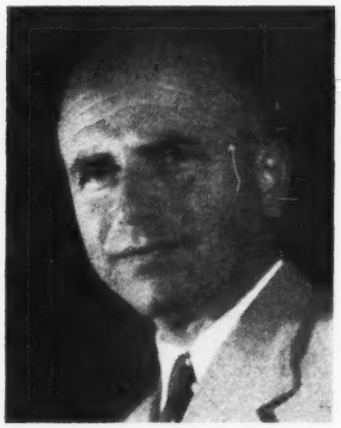
At the present time, Mr. Pierson is in the employ of the Humble Oil & Refining Company in the capacity of a Research Geophysicist.

He is a member of Tau Beta Pi, Eta Kappa Nu, the American Institute of Electrical Engineers, and the Institute of Radio Engineers.

R. L. SENGBUSH

R. L. SENGBUSH received a Ph.B. degree in Physics and Mathematics from the University of Wisconsin in 1944. He served in the U. S. Navy for two years as an electronics officer. He was employed by the Field Research Laboratories of the Magnolia Petroleum Company in 1947, and has worked on their Research Seismograph Crew as observer, computer and presently as party chief. He is a member of the Society of Exploration Geophysicists and an associate member of the American Association of Petroleum Geologists.

M. UNZ studied Electrical Engineering at Darmstadt Technical University until 1924 and received his Dr.Eng. degree in 1931. From 1924–27 he was on the construction staff of the Hebrew Technical College, Haifa. Later on he was engaged in the development of electrical measuring apparatus. In 1933 he joined the Engineering Department of the Iraq Petroleum Company. Since 1950 he has been attending to an operational ground water survey with the Technical Division of the Mekoroth Water Company. Dr. Unz is a member of the Association of Engineers in Israel and Associate Member of the Institution of Electrical Engineers.



M. UNZ

J. E. WHITE

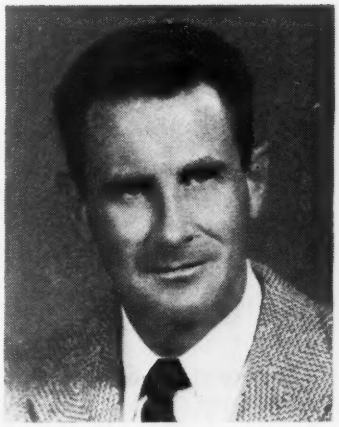
J. E. WHITE received a B.A. degree in 1940 and an M.A. degree in 1946, both from the University of Texas. He received a Ph.D. from the Massachusetts Institute of Technology in 1949. The major subject in each case was physics.

From 1941 to 1945, Dr. White worked on underwater sound problems at the Massachusetts Institute of Technology, serving as director of the MIT Underwater Sound Laboratory during the last year of this period. He then spent one year in guided missiles research at the Defense Research Laboratory in Austin before returning to MIT for graduate work. He joined the Field Research Laboratories of the Magnolia Petroleum Company in 1949, where he has charge of a group doing research in geophysics.

Dr. White is a member of the Society of Exploration Geophysicists, the Acoustical Society of America, and the American Crystallographic Association.

CONTRIBUTORS TO OCTOBER, 1952, GEOPHYSICS

These biographies were received too late for publication in the issue containing papers by the respective contributors.



C. F. ALLEN

C. F. ALLEN received his A.B. in geology from the University of California in 1939. After a year of graduate work, he joined Superior Oil Company as a geologist. In 1942 he resigned to work for Western Geophysical Company, where he became a seismic party chief. In 1947, he left Western and shortly thereafter joined the Stanford Research Institute as a geologist and geophysicist. His work since then has included experimental seismic programs in West Texas and New Mexico, and the seismic mapping of parts of the Taku Glacier, in Alaska.

Mr. Allen is an associate member of the AAPG and a Fellow of the American Geographical Society.

RICHARD LOUIS CALDWELL

RICHARD LOUIS CALDWELL received a B.S. degree in Physics from the Louisiana State University in 1939 and was a graduate assistant in physics there for two years receiving the M.S. degree in June 1941. From 1941 until October 1945 he worked as a physicist for the Naval Ordnance Laboratory, Washington, D. C. In November 1945 he accepted a part-time assistant instructorship in physics at the University of Missouri and in February 1946 resumed his graduate studies in physics at that university. In February 1948 he was granted an O. M. Stewart Fellowship to do his doctoral research at the Argonne National Laboratory, Chicago, Illinois and received his Ph.D. degree in Physics in June 1949. In August 1949 he joined the Magnolia Petroleum Company's Field Research Laboratories in Dallas, Texas, where he is presently working in their Geophysical Prospecting activity. Memberships include Phi Kappa Phi, Sigma Xi and Dallas Geophysical Society.

JOHN L. KELLY, JR.

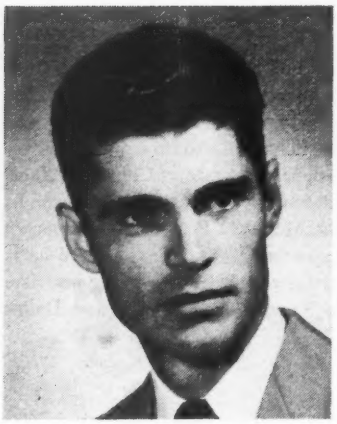
JOHN L. KELLY, JR. was born December 26, 1923, in Corsicana, Texas. He graduated from Austin High School in 1940 and entered the University of Texas. He withdrew from that school in 1942, worked for the Army Map Service until June of 1943, and entered the service of the U. S. Navy. In 1947 he returned to the University of Texas where he received his Master's Degree, majoring in physics in 1952, and is at present working toward his Doctor's degree.

HAROLD O. SEIGEL graduated from the University of Toronto in 1946 with a B.A. in Applied Mathematics. He received his M.A. in Applied Mathematics in 1947 and the degree of Ph.D. in Geophysics from the same university in 1049.

Since 1949 he has been Assistant Manager and Chief of Interpretation, Geophysical Department, Newmont Exploration Limited, Jerome, Arizona.

Dr. Seigel is a member of the Society of Exploration Geophysicists and of the American Geophysical Union.

HAROLD O. SEIGEL



HENRY C. TOWLES, JR.

HENRY C. TOWLES, JR. received his B.S. degree in civil engineering from Southern Methodist University in 1945. Following this he served as an Ensign, Civil Engineer Corps, U. S. Navy, and upon completion of this tour of duty returned to S.M.U. as an instructor of civil engineering. He was employed by Garrett Exploration Company in 1947, and later by their successors, the Geotechnical Corporation in their department of interpretation and review. In 1949 he was employed by Rayflex Exploration Company where his duties were velocity analysis and final report presentation. Concurrent with this he completed work toward the M.S. degree in geology at S.M.U. in 1951. Since March, 1951, he has been a party chief with the Rayflex Exploration Company. He is a member of the Society of Exploration Geophysicists and an associate member of the American Association of Petroleum Geologists.

W. M. WELLS graduated from the Colorado School of Mines in 1933 with the degree of Geological Engineer, having majored in geophysics. He worked for a year as an instrument man in the U.S.C. & G.S., and in 1934 was employed by the Seismograph Service Corporation as an observer. In 1936 he was employed by Arkansas Fuel Oil Company as an observer and later became party chief of both seismic and gravity crews. In 1941 he resigned to become process engineer for Remington Arms Company at the Denver ordnance plant, returning to Arkansas Fuel Oil Company in 1942 as a geophysicist. He was gravity meter contractor from 1945–1947, when he joined Engineering Laboratories as assistant sales manager in charge of all seismic instrument sales. In 1949 he became associated with the Institute of Inventive Research on the development of the Poulter Seismic Method. He is now employed by the Stanford Research Institute as a geophysicist. Mr. Wells is a member of the Society of Exploration Geophysicists.

W. M. WELLS

M. R. J. WYLLIE

M. R. J. WYLLIE was born in Cape Town, South Africa, July 31, 1919. Educated at the South African College School, matriculating in 1935. University of Cape Town, 1935–1939, B.Sc. (Applied & Industrial Chemistry) 1939. South African Rhodes Scholar at Magdalen College, Oxford, 1939–1942, D.Phil., 1943. Volunteered for service in Royal Naval Volunteer Reserve, 1942. Transferred to South African Navy in 1943 and seconded to Royal Navy. Lent to Royal Indian Navy in 1944; Lieutenant-Commander. Served with Department of Miscellaneous Weapons Development, Admiralty, 1942–1944 and 1946. Deputy-Director, Admiralty Research and Development (India) 1944–1945. Courtesy Fellow, The Johns Hopkins University, 1946–1947. Joined Gulf Research & Development Company, 1947. Now Head of Petrophysics Section, Geology Division.

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MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the society. This publication does not constitute an election but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the president within thirty days. Names of the references appear in parentheses after the name of each candidate.

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See additional applications on pages 267–268.

PAPERS PRESENTED AT THE EASTERN CANADA MEETING
KING EDWARD HOTEL, TORONTO, ONTARIO
OCTOBER 27–28, 1952

A Review of Magnetic Interpretation Techniques

JAMES AFFLECK

The purpose is to review established methods of interpreting magnetic surveys. The advantages and limitations of the magnetic method are described. While the emphasis is on exploration for petroleum, the utilization of the techniques in the search for metallic minerals is discussed.

The Applications of Multiple Frequency Electromagnetic Exploration to Mining

S. H. WARD

A variable frequency electromagnetic exploration technique has been devised which, theoretically, will provide information concerning the physical properties and dimensions of buried conductors of electricity. Two field tests were conducted, one in the Sudbury area at the Mount Nickel orebody of Falconbridge Nickel Mines Ltd., and the other at the Radenhurst-Caldwell magnetite deposit in the Grenville sub-province of Ontario.

The purpose of the Mount Nickel experiment was to ascertain the change of response with frequency of a typical sulphide body, and to illustrate the amount of useful information which might be obtained with an electromagnetic system in which the intensity and phase of three components are measured. It was found that information regarding dip, depth, plunge and electrical conductivity was much more reliable than that obtained by other geophysical techniques.

The field tests at the Radenhurst-Caldwell property were made for the purpose of determining the feasibility of applying the variable frequency electromagnetic technique to the problem of estimating the percentage iron in a magnetite deposit. A new theory indicates that this can be done quite reliably, because measurements are influenced by two physical properties—electrical conductivity and magnetic permeability. The experiments have shown that phenomena predicted theoretically actually are found in the field. The results are sufficiently encouraging to suggest that it will be possible to make reliable estimates of percentage iron.

The results of the two field trials indicate that the variable frequency technique will have at least two important applications. The reliable estimation of the percentage iron of magnetite deposits is the most promising. It also appears possible to distinguish between massive and disseminated sulphides. Eventually it may be possible to distinguish between graphitic shears and sulphide mineralization. However, more field tests are required to permit a reliable correlation between physical and geological conditions.

Effects of the Electrical Constants of the Ground on Radio Wave Propagation

JAMES R. WAIT

A descriptive review is given of the author's theoretical investigation of the influence of the conditions of the ground on the propagation of radio waves. It is indicated that discontinuities of the conductivity and dielectric constant of the ground at depths down to sixty feet can modify the characteristics of the propagation at frequencies of 100 Kcs. Curves showing the magnitude of the "wave tilt" of radio waves for a horizontally stratified earth are given. Limitations of radio wave prospecting are outlined.

An Analysis of Airborne Surveying for Surface Radioactivity

J. C. Cook

Improved calculations of the gamma radiation field intensities expected from "typical" outcrops of radioactive ores, and from a flat earth composed of normal rocks and soils are given. It is found that the "background" flux or intensity should normally vary between 0.3 and 7 hard gamma rays per second through a 1 cm^2-cross section sphere, depending on elevation and local soil composition. The anomalies from "typical" ore outcrops should not be distinguishable from such normal variations, above an area of variegated exposures, at flying heights much greater than 30 feet. Rough topography or atmospheric radon may give serious interference above 100 feet or so. Detecting instrumentation should have a response time below 1 second and a product (cross section×efficiency) exceeding 40 cm^2 for flight at 30 feet, or very much greater for higher flight. A number of other considerations are discussed briefly.

Geothermal Investigations at the University of Western Ontario

Robert J. Uffen

The application of the modern theory of solids to the determination of the thermal properties of the earth's interior is reviewed. Methods of estimating the adiabatic and melting point gradients; and the variation with depth of the specific heats, thermal expansion and thermal conductivity are given. Some causes of anomalous temperatures in the earth's crust are discussed. The magnitudes and distribution of the anomalous temperatures are computed for a few idealized geological structures. It is found that high grade radioactive ore deposits, and deposits undergoing rapid oxidation offer the greatest possibility of successful detection by sub-surface temperature surveys. Recent developments in the use of thermistor resistance thermometers and thermal conductivity "probes" are discussed.

A Conducting Ferro-Magnetic Sphere in the Presence of a Coil Carrying an Oscillating Current

James R. Wait

The problem of a conducting sphere of arbitrary electrical properties, in the presence of a solenoidal coil carrying an oscillating current is investigated. Expressions are developed for the secondary magnetic field components where there is no restriction on the size of the solenoid relative to the sphere. The results of computations for the strength of the induced multipoles are given in graphical form.

PAPERS PRESENTED AT THE PACIFIC COAST MEETING
STATLER HOTEL, LOS ANGELES, CALIFORNIA
OCTOBER 31, 1952

Safety Is Important to Geophysics

Bart W. Sorge, United Geophysical Company

Geophysicists hold almost all responsible positions in geophysical exploration. As a result, they are responsible for the safety of workers under their direction. The Committee on Safety of the Society has made a study of reports to the Geophysical Accident Information Exchange. Much information has been accumulated that formerly was not available and which will be of benefit to geo-

physical operators. Evidence shows that well-coordinated safety efforts are worthwhile and that cooperative efforts within the industry in the cause of safety and accident prevention have been successful. A recently produced safety film, DRILLING THE SAFE WAY, will be shown.

Curved-Ray Delta-T Analysis

JOHN T. BRUSTAD, Western Geophysical Co.

The quantity $K=\frac{S^2T}{2(M^2+2MT)}$, where T is the reflection time at zero offset, $T+M$ (the reflection time at an offset of S feet), which in straight path delta-time analyses is taken equal to $\frac{1}{2}Va^2T$, is actually a close approximation of $\int_0^{1/2T} v^2dt$. The distance between successive reflecting horizons, under the assumption of constant velocity in the interval, is then given by the square root of the product of the increment in K by half the increment in reflection time. The depths and average velocities calculated by this method will, in most cases encountered in practice, be accurate to within $\frac{1}{2}$ of 1 percent of theoretical, and, in any case likely to be encountered, be not less accurate than those calculated by the straight-path method.

Aerial Shooting for Seismic Exploration

J. J. JAKOSKY, International Geophysics, Inc.

This paper describes developments in a new technique for air shooting.

A brief historical résumé is given of early work in the use of explosives placed at a height above the earth comparable to the depth of the reflecting bed below the surface, and of the more recent work with the explosives placed close to the surface of the earth to utilize the super-sonic wave energy.

The subject technique uses an explosive bomb which is ejected from a mortar placed on the surface of the ground. The bomb is exploded at a specific height, which is a function primarily of the spread length and near-surface ground velocity, in order to minimize the detrimental effects of ground-roll and reverberation which have created such serious obstacles in previous air shooting techniques. The apparatus and bombs, and general theoretical factors are described.

Records are shown comparing the recordings from in-hole shooting with air-shots at the same shot-point, at various difficult drilling areas in the United States.

Notes on the Use of Multiple Geophones

LEONARD V. LOMBARDI, Stanford Research Institute

The use of multiple geophones, which has been largely empirical, serves two primary functions: cancellation of random and other unwanted energies, and improved sampling of the wave front. Curves are presented showing surface wave cancellation effectiveness of several different spreads. The results also apply to mixed records. Cancellation of random energies follows conventional sampling theory, varying with the square root of the number of geophones in the spread. Sampling of the wave front is more complex because the samples are not mutually independent.

A Model for Lamb's Problem in the Presence of Internal Viscosity

MARGERY NEWLANDS and LEON KNOPOFF, U.C.L.A. Institute of Geophysics

A seismic model for Lamb's problem has been constructed. A localized, nor-

mally directed force is supplied to a slab of microcrystalline wax by a pulsed $LiSO_4$ crystal unit and the quasi-steady state results are obtained by means of an oscilloscopic record. Experimental results are compared with theoretical work incorporating the property of a viscosity of the Stokes type in the original problem of Lamb. The computation yields a definite wave pattern for sufficiently remote observations and the dispersive and absorptive nature of the wave motion is given as a function of the parameter $r\alpha/v$ involving the focal distance, the velocity of compression waves and the kinematic viscosity. Tentative values for the physical properties of the wax are essayed from the computation.

Seismic Model Study

E. T. HOWES, L. H. TEJADA-FLORES, and L. RANDOLPH, United Geophysical Company

A method has been developed for studying seismic reflections in reduced scale which simulates geophysical seismic exploration methods. Use is made of a tank of water for transmission of the acoustic wave from a source to a faulted limestone stratum and return to a receiver.

Details of equipment used and slides diagramming the various details along with oscillogram slides of acoustic reflection waves are included.

Geophysical Comparisons at Dinuba

M. C. BORN, Amerada Petroleum Corp.

A structural anamoly near Dinuba, California is inferred from four different geophysical surveys and a core hole program. The similarity in contoured results of the applied methods is unique in exploration history. Some idiosyncrasies in comparing geophysical maps are briefly discussed.

PAPERS PRESENTED AT THE SIXTH ANNUAL MIDWESTERN MEETING HOTEL TEXAS, FORT WORTH, TEXAS NOVEMBER 13–14, 1952

What Is a Geophysicist?

CURTIS H. JOHNSON, President of the Society of Exploration Geophysicists. General Petroleum Corporation, Los Angeles, California

The above is too common a question from the public at large. With science in the public eye, as it has been since the advent of the atom bomb, Geophysics, and the Earth Sciences generally must step up their effort for recognition in competition with nuclear physics and other branches of science or they will find themselves on the short end of the appropriation wish bone; in the shallow end of the manpower pool;—their personnel overworked and frustrated.

Appropriations, whether from governmental agencies, educational endowments or in the shape of budget allocations by industry, are important to permit expansion of personnel and equipment, but the principal bottle-neck limiting the effectiveness of geophysics and geophysicists is a shortage of manpower.

It is proposed that Public Relations is broadly the tool to use in building up a manpower supply. Through Public Relations activities, the public, which is the source of our manpower, may be made aware of the importance and attractiveness of the Geophysical Profession as a career. Students may be aided through vocational guidance, scholarships, summer employment programs, job procurement, Student Section encouragement and the "Big Brother" or "Buddy" System. Educational institutions and faculties may be aided by curriculum con-

ferences, visiting lecturers, research grants and the above Student Services. The S.E.G. may help attain these objectives through cooperation with the American Geological Institute, through its own actions at national, local and member levels, and through its contacts with exploration managements. Immediate launching and continued pushing of these S.E.G. activities in cooperation with the A.G.I. and at national, local, and individual levels is strongly recommended.

Geophysical Exploration—Operation Main Brace

W. Dow Hamm, The Atlantic Refining Company, Dallas, Texas

Exploratory Activity—Permian Basin

H. L. Swords, Union Oil Company of California, Midland, Texas

Seismic activity in the Permian Basin shows a slight decline after reaching a peak of 135 crews in May. Some 65 seismic crews are now operating in West Texas and 45 in southeastern New Mexico. Drilling activity has also declined considerably due primarily to the steel strike and to disappointing results in the Spraberry.

Most important discoveries of the year have been made in eastern Andrews County in the Midland Basin and in northern Lea County. Present developments in the Delaware Basin are attracting widespread interest. Deep wells now drilling will determine the value of the Delaware Basin as an oil province.

Unconformities Associated with Oil Accumulation, Denton Pool, Lea County, New Mexico

Ralph H. Fellows, The Atlantic Refining Company, Lovington, New Mexico

The prolific, dual-pay Denton Pool is located on a north-south trending anticline in the southeastern portion of New Mexico. Evidence is presented to show that the unconformities beneath the Wolfcamp and at the top of the Siluro-Devonian sequence created favorable reservoirs which have been subsequently occupied by oil.

Wavelet Contraction, Wavelet Expansion, and the Control of Seismic Resolution

Norman Ricker, The Carter Oil Company, Tulsa, Oklahoma

This paper discusses the transmission characteristics of seismic apparatus for distortionless reproduction of seismic wavelets. It is shown that, by suitable design of seismic apparatus, the individual wavelets which go to make up a seismogram may be contracted or expanded without altering the relative arrival times of the wavelet centers. By means of this procedure the resolving power of the seismic apparatus may be increased or decreased at will, within certain limits. Laboratory studies of the performance of the wavelet contractor are described and field seismograms made with the wavelet contractor also are displayed.

Geophysical Reconnaissance of the Middle Amazon River Valley

Neil W. Mann and K. E. Burg, Geophysical Service Incorporated, Dallas, Texas

The large geological basin located in the Middle Amazon River Valley is outlined by the early Pre-Cambrian crystalline basement complex. The surface of the basin is composed of continental Tertiary deposits, the eastern extension of the basin being the only area where Paleozoic rocks are visible in the outcrops.

The center of the basin is located some twelve hundred miles upstream from the mouth of the Amazon. Its remote location and the lack of transportation and communication facilities have introduced many unusual problems. Special field techniques and equipment were developed which are described and illustrated with color slides.

The carefully planned exploration program in this remote basin is an excellent example of an orderly development of a virgin area where previous geological knowledge was almost totally lacking.

Refraction seismic methods were used to outline the basin and to ascertain the depth of several marker horizons. Several refraction anomalies were detailed by reflection methods. The refraction results show that the basement is quite shallow in most of the basin, its greatest depth being less than 10,000 feet.

Gravity Measurements and Their Interpretation in South America Between the Latitudes of 15° and 33° South

PAUL C. WUENSCHEL

The results of two gravimetric profiles that extend completely across the continent of South America between latitudes 15° and 33° South and their extension to sea across the continental margin into the ocean basins are presented.

A two-dimensional interpretation was made of the gravity field along each profile. The crustal model used in this interpretation is similar to that suggested by Heiskanen in 1932 and further modified to satisfy the present seismic knowledge of the structure of ocean basins and of continents. The direct method of gravity interpretation has been used which makes it possible to construct a cross section of the upper 70 kilometers of the earth's crust.

This two-dimensional analysis indicates a negative isostatic anomaly on the landward side of the submarine trough paralleling the west Coast of South America, and a positive isostatic anomaly over the outer ridge to the west of the trough. The Oriental Andes and the Coastal Range are undercompensated with the Parana Basin and entire east coast overcompensated. The midcontinent is slightly undercompensated.

A negative over the Occidental Andes and Altiplano is attributed to low-density volcanics and continental sediments. The negative over the submarine trough along the west coast is attributed to sedimentary fill rather than the traditional down buckle of sialic rock into the simatic substratum. Geological evidence is presented to substantiate these interpretations.

Oil and Gas Exploration in Alabama, Georgia, and Florida

ROBERT B. BAUM, Seismograph Service Corporation, Shreveport, Louisiana

The discovery of the Pollard field in southern Alabama early in 1952 sparked a campaign of leasing and exploration which spread quickly into Georgia and Florida. Three fields in southwestern Alabama and one in southern Florida account for all the oil production in the three states.

Some aspects of the general geology and geophysics of the area are discussed. Maps, cross sections, and correlation charts are presented suggesting the presence of geologic conditions favorable for possible oil and gas production.

Early seismic exploration in much of the area was not effective, as near-surface conditions appeared to affect seismic response adversely. In recent months the tempo of seismic activity has been accelerating, and improvements in instrumental and interpretive techniques are being achieved through current experi-

mental work. Examples of representative reflection records and a seismic cross section showing the Pollard field fault are presented.

Wave-Front Charts and Ray-Path Plotter

ALBERT W. MUSGRAVE, Magnolia Petroleum Company, Dallas, Texas

A study of isovelocity surface configurations and their effect on the wave fronts and ray paths of seismic energy is summarized. The cases that can be solved by dip plotters and charts are pointed out.

A discussion of velocity assumptions indicates that the linear increases of velocity with time, $V = Vo + aT$, has two advantages: 1) it comes nearer to fitting most empirical cases, and 2) it is easier to determine the constants necessary to fit it to empirical data. The basic equations and relations are presented.

The methods of obtaining the constants necessary for plotting wave-front charts are shown along with the specialized charts. These charts are now available at the Colorado School of Mines Research Foundation, made by the use of the Raypath Plotter developed by the author while obtaining his doctor's degree.

Safety Is Your Responsibility

BART W. SORGE, United Geophysical Company, Pasadena, California

The geophysical industry's safety record compares unfavorably with industry in general and the petroleum industry in particular. There also exists a decided difference in safety performance between oil-company-operated geophysical crews, as a group, and those operated by contracting organizations. This represents a real challenge to the geophysical industry, as ways and means must be found to improve the safety and accident-prevention performance. We must accept this challenge in order to avoid possible future regulation by government agencies.

Accident Costs Can Be Reduced Through Industry Cooperation

J. DOYLE SETTLE, American Association of Oil Well Drilling Contractors, Dallas, Texas

The effect of an industry-wide coordinated accident-prevention program on accident rates in the drilling industry where the problems encountered are very similar to those in geophysical operations is reviewed.

Essentials of a Safety Program for Geophysical Contracting Companies

W. H. NEWTON, General Geophyiscal Company, Houston, Texas

The basic requirements of a successful safety program for the small company will be discussed.

A Demonstration of Some Serious Hazards That Are Peculiar to Geophysical Operations and Some Suggested Ways to eliminate These Hazards

G. M. KINTZ, U. S. Bureau of Mines, Dallas, Texas

Interpretation Method for Well Velocity Surveys

DEAN WALLING and CARL H. SAVIT, Western Geophysical Company, Los Angeles, California

Well surveys often suffer from the problem of "cable lead" and other extraneous energy arrivals. All of the energy arrivals at the well seismometer may be

individually timed by the use of phase differences occurring in differing amplifier filters. Special shot-hole patterns and a simple graph enable the interpreter correctly to identify all energy paths. No new equipment or instrumentation is needed. Laboratory tests and an actual survey illustrate the method.

Core Hole Velocity Surveys

RICHARD BREWER and J. B. H. HENDERSON, The Atlantic Refining Company, Shreveport, Louisiana, and Survey Drilling Company, Dallas, Texas

In keeping with the increased need for more detailed near-surface seismic velocity information, a method for conducting velocity surveys in exploratory core holes has been developed. The method is described in this paper, and results from velocity programs in North Louisiana, South Arkansas, and North Dakota are discussed.

A Review of Exploration and Development in the Uinta Basin, Utah

VERNE E. FARMER, JR., The Carter Oil Company, Vernal, Utah

Despite the innumerable surface indications of hydrocarbons, it was not until 1945 that any major oil company began a conscientious exploration program in the Uinta Basin.

Reconnaissance gravity and seismograph work was begun in the early stages of this effort and the volume of such work increased rapidly and steadily for the next several years. Complex stratigraphy and lack of sub-surface control has greatly complicated seismic interpretation.

The first discovery in the Uinta Basin was the Roosevelt Pool in 1949. This field produces primarily from fractures at a depth of between 9,000 and 10,000 feet. The Duchesne and Red Wash pools were opened in 1951, and at the present two potential discoveries are awaiting evaluation.

Although wildcat drilling in the area has reached an all-time high this year, by the end of 1952 it is expected that the dry-hole density will still be about one well for each 160 square miles.

Exploration History (Prior to the Cotton Valley Discovery) of the Ruston Field, Lincoln Parish, Louisiana

J. RYAN WALKER, Arkansas Natural Gas Corporation, Shreveport, Louisiana

The first exploration to indicate the presence of a structural feature in the Ruston field area was a reconnaissance surface survey by the Arkansas-Louisiana Gas Company in 1931. This paper, with maps, describes the surface work and subsequent reflection seismograph surveys conducted by Arkansas-Louisiana Gas Company in the area prior to the discovery of gas in the Cotton Valley formation. A comparison of the results of the surface and seismic work is made with the structure as revealed by present subsurface control.

Problem Areas for the Seismologist

GLENN M. CONKLIN, Sun Oil Company, Dallas, Texas

Interpretative problems encountered in four widely scattered areas, South Florida, Beaver County, Oklahoma, the Plainview Basin of the Texas Panhandle, and Hancock County, Mississippi, are discussed.

Secondary refraction records, shot in Okeechobee County, Florida, offer problems because of the low-velocity energy being sustained for long periods of time. This low-velocity energy distorts and obliterates the high-velocity events.

Velocity problems due to differential salt solution in the Blaine-Cimarron interval in Beaver County are considered. Records are shown which illustrate the distortion of events and the resultant problems.

Multiple reflections give trouble in the Plainview Basin of the Texas Panhandle. Record sections showing the many multiples are shown and discussed.

Multiple reflections in Hancock County, Mississippi, are discussed and record sections and cross sections are shown.

Some suggestions for the treatment of the problems are advanced.

Gravity Case History: Dawn No. 156, Ontario

RICHARD A. POHLY, Seismograph Service Corporation, Tulsa, Oklahoma.

The Dawn 156 Pool in southwestern Ontario was discovered by the Union Gas Company of Canada, Ltd., in January, 1952, by drilling on a gravity maximum. The drilling supported the original interpretation that this maximum was produced by a Silurian reef. Initial production of 6.5 million cubic feet per day was obtained from the upper fourteen feet of the Guelph in highly porous reef dolomite at a depth from 1,720 to 1,734 feet below the surface.

The geology of the area is discussed as a background for the gravity interpretation. Bouguer and residual gravity maps of the original survey are presented.

Evaluation of Anomalies by Derivatives

H. WAYNE HOYLMAN, Hoylman-Morris, Consultants, Los Angeles, California

Use is made of second and fourth derivatives in the delineation and evaluation of anomalies in aeromagnetic surveys. The second derivative provides delineation on a regional basis, whereas the fourth derivative provides a semi-detailed delineation plus a statistical rather than a personal evaluation of anomalies. Correlation is shown of typical fourth derivative anomalies with three Devonian oil fields in eastern New Mexico.

Seismic Recording on Magnetic Tape

G. B. LOPER and R. R. PITTMAN, Magnolia Petroleum Company, Dallas, Texas

A system of recording and reproducing exploration seismograms on magnetic tape is described. Geophones and amplifiers with broad-band response, approximately 4–300 cps, are used to channel the seismic signals to a 13-track tape recorder. The magnetic tape is 1-inch wide. Some narrowing of the band-width at both high and low frequency ends is done to suit the particular studies to be made. One of the tracks is used to record a time reference signal. Each broad-band recording is formed into an endless loop and played back in repeating fashion. The signals are fed through a flexible system of filtering and mixing, then examined on the screen of a 12-trace cathode-ray oscilloscope of 12-inch diameter. The sweep of the oscilloscope is synchronized with the loop and, by varying the sweep speed, the entire record, or an expanded portion thereof, is held stationary on the screen. Conventional paper records of the reproduced, modified record are finally made with a regular seismic camera.

Geophysical Models

ROBERT DAVENPORT, Texas Seismograph Company, Wichita Falls, Texas

All the significant data on seismic records are incorporated in three-dimensional models. The geophysical data are drawn on sheets or ribbons of clear plastic

in a cross-section manner. The sections or ribbons are assembled in their respective vertical and horizontal positions and secured by means of scotch tape or plastic cement to form the models. Various colored inks, dyes, and paints aid in making correlations outstanding. Geological data and well logs are very easily added to the geophysical models.

Several different types are shown and described, both for permanent erection and those that can be folded or rolled up and stored in a standard file cabinet.

This paper intends to show how the geophysical models offer practical presentations of the ever-increasing complexities and amounts of geophysical data that the industry looks forward to analyzing.

ANNOUNCEMENTS

SEVENTH ANNUAL MIDWESTERN EXPLORATION MEETING

This title has been chosen for the annual joint meeting of the society's local sections in Dallas, Fort Worth, Midland, Shreveport, and Tulsa. The recently-formed Geophysical Society of Oklahoma City has been invited to join in the next meeting, scheduled for the Adolphus Hotel, Dallas, Texas, on November 12 and 13, 1953. The Permian Basin Geophysical Society, Midland, will be in charge of arrangements and program. This advance announcement is made to assist company management in scheduling attendance by their employees.

PROPOSED AMENDMENTS TO THE BYLAWS

According to the Constitution, Article XVII, Section 1, "The Council shall make such Bylaws not in conflict with the Constitution, as it may deem necessary for the proper government of the Society. The Council may amend the Bylaws at the annual joint meeting by an affirmative vote of two-thirds of the members of the incoming Council present. All proposed amendments must, however, be published in the Society's Journal before being submitted to the Council." The Executive Committee, assisted by the Special Committee on Constitution and Bylaws, has approved for submittal to the Council the following amendments to the Bylaws:

Article I, Section 5. In the first and second sentences, substitute "$4.50" for "$3.00."

Article VII, Section 5. Delete the sentence, "The candidates shall be listed side by side."

Article X,

Section 1. Delete all after "(j) Standing Committee on Reviews"; and substitute "(k) Standing Committee on Public Relations; (1) Standing Committee on Publicity; (m) Standing Committee on Geophysical Activity; (n) Standing Committee on Saftey."

Section 4. After "active" in the first sentence, insert "or honorary." Delete the last sentence and substitute the following: "The Committee shall actively solicit applications for membership from those qualified. It shall work closely with the membership committees of the local sections."

Section 5. After "active" in first sentence, insert "or honorary."

Section 6. After "active" in the first sentence, insert "or honorary."

Section 7. In the first sentence, delete "Active members" and substitute "members of any class."

Section 8. In the first sentence, delete "active members" and substitute "persons." After the first sentence, insert the sentence, "The Chairman shall be an active or honorary member."

Section 9. In the first sentence, delete "active members" and substitute "persons." After the first sentence, insert the sentence, "The Chairman shall be an active or honorary member."

Section 10. In the first sentence, delete "active members" and substitute "persons." At the end of the third sentence, after "President," add "and shall be an active or honorary member."

Section 11. After "active" in the first sentence, insert "or honorary."

Section 13. In the first sentence, delete "and publicity." In the last sentence, delete "and shall

prepare and arrange for the distribution of suitable publicity material for the press and radio" and substitute "shall recommend public relations policy, and shall carry out projects to promote good public relations."

Section 14. Replace the present wording of this section by the following: "The Standing Committee on Publicity shall consist of a Chairman, appointed for one year by the President, and such additional members, appointed for one year by the Chairman, as he may deem desirable. The Committee shall prepare and arrange for the distribution of suitable publicity material for the press, radio, and other appropriate media."

Section 15. This new section shall read the same as the former Section 14 except that in the first sentence, "or honorary" shall be inserted after "active."

Section 16. This new section shall read as follows: "The Standing Committee on Safety shall consist of a Chairman, appointed for one year by the President, and such additional members, appointed for one year by the Chairman, as he may deem desirable. The Committee shall recommend safety policy and shall carry out projects to promote safety in geophysical operations."

CREST CONTEST WINNER

A life membership in the society has been awarded to William W. Butler, geophysical supervisor for the Tide Water Associated Oil Co., Houston, Texas, for submitting the winning design in the

contest to obtain an official crest for the Society of Exploration Geophysicists. The award was presented at the Midwestern Regional Meeting on November 13, 1952, at Fort Worth, Texas, by President Curtis H. Johnson.

The design, chosen by the Standing Committee on Honors and Awards from fifty-five entries, consists of a Western Hemisphere map framed by the traditional Mariners' Compass. In describing the symbolism of the design Mr. Butler said that although more than 3,500 exploration geophysicists throughout the world belong to the society, its birthplace is Houston, and the largest concentrations of the membership are in the Western Hemisphere. The globe map is used to signify that geophysics is the science of the earth, and the Mariners' Compass denotes the fact that the science of geophysics is used to explore the earth and its crust in search of mineral wealth.

WILLIAM W. BUTLER was graduated with honors from The University of Colorado in 1932 with a B.S. Degree in electrical engineering and elected to membership in Tau Beta Pi, Sigma Tau, and Eta Kappa Nu engineering organizations.

His initial geophysical work was in 1934 as a computer and later a chief computer for the Geophysical Research Corporation after being employed in the engineering department of the United Power and Light Company for approximately two years. In 1937 he was employed by Barnsdall Oil Company as a chief computer and was soon made assistant to the chief geophysicist, making review interpretations and developing computation techniques. Upon the decision of the Barnsdall Oil Company to discontinue the operation of its own geophysical parties, preferring a more flexible operation employing contract parties, he was employed by the Gulf Research and Development Company during the years 1941 to 1944 as a seismic interpreter in the geophysics division at their Pittsburgh Laboratory and later on a field seismograph party. He was in the employ of The Superior Oil Company of California as a party chief between 1944 and 1945.

Mr. Butler has been employed for the past seven years as a geophysical supervisor for the Tide Water Associated Oil Company. He is also a member of the Houston Geological Society and the Houston Section of the S.E.G.

UNIVERSITY OF TORONTO STUDENTS ORGANIZE

On Tuesday, October 28, 1952, the Geophysics students of the University of Toronto met and formed a student society, to be called the University of Toronto Geophysical Society. Plans are under way to petition the S.E.G. for affiliation as a student chapter of the Society of Exploration Geophysicists.

There were about twenty students present, graduate as well as undergraduate, along with a number of distinguished guests; for the date was chosen to coincide with the Eastern Regional Meeting of the S.E.G. and a number of the prominent visitors came and met the students. Several of the guests addressed the students, including President Curtis H. Johnson and Past Presidents E. A. Eckhardt and R. D. Wyckoff, along with Bart W. Sorge, Charles H. Moore, Jr., Fred Agnich, Robert Dyk, J. Tuzo Wilson, and Lachlan Gilchrest. Also present were Ralph C. Holmer, R. B. Ross, Colin C. Campbell, and P. N. S. O'Brien. Don Russell acted as chairman.

Elections were held for officers of the new society. Tom Gledhill, III Physics and Geology, was elected President; Dave Rostoker, III Physics and Geology, Public Relations Officer; and Geoff. Oldham, Graduate Studies, Secretary-Treasurer.

After a short formal program, there followed a long period of interesting, informal discussion between the guests and the students. In all, the meeting was encouraging, and with the support promised by the S.E.G. the Society can look forward to a promising future.

DAVID ROSTOKER
Public Relations Officer

Toronto, Ontario, Canada
October 31, 1952

AERO-MAGNETIC MAPS OF CANADA

The Geological Survey of Canada has recently informed the Editor that a system has been inaugurated whereby interested persons may receive notice in advance of the date on which aeromagnetic maps will be available for distribution. Purpose of this special notice is to permit anyone to place his order for these maps in advance of the release date or to obtain them personally on that date.

Correspondence should be directed to W. A. Bell, Director, Department of Mines and Technical Surveys, Geological Survey of Canada, Ottawa, Ontario.

For example, Geophysics Paper 77 was released September 19 at 9:30 A.M. from Room 308, National Museum Building, McLeod Street, Ottawa. The paper dealt with an aero-magnetic map designated Sandy River, District of Mackenzie, Northwest Territories, Lat. 60–30 to 60–45; Long. 115–30 to 116–00. Scale 1 inch to 1 mile, price 25 cents.

KODACHROME SLIDES ILLUSTRATING A CAREER IN GEOPHYSICS AND GEOCHEMISTRY FOR LOAN

The Division of Geophysics and Geochemistry of The Pennsylvania State College has prepared a set of 42 2×2″ kodachrome slides to illustrate the opportunities for a career in geophysics and geochemistry. A mimeographed text explaining the slides accompanies them and is designed to be read while they are being projected. The reading time is 22 minutes. This material was prepared primarily for circulation to high schools for use in guiding young men and women in selecting a college curriculum. It can be borrowed free of charge by any responsible organization from the Chief, Division of Geophysics and Geochemistry, Mineral Sciences Bldg., State College, Penna. In requesting the slides, please state date wanted (give several choices if possible), expected size of audience, and its nature (students, professional groups, etc.). Eleven other sets of slides covering all the other fields of Mineral Industries are being prepared.

DAVID M. DELO BECOMES PRESIDENT OF WAGNER COLLEGE

Assuming office July 1, 1952, Dr. David M. Delo became the sixth president of Wagner College since the school was moved from Rochester, New York, in 1918. Educator, author, and geologist, Dr. Delo came to Wagner from Washington, D. C., where he had been executive director of the American Geological Institute and executive secretary of the Division of Geology and Geography of the National Research Council.

As Chief of the Scientific Manpower Branch in the General Staff's Research and Development Division, Department of the Army, from 1946 to 1949, Dr. Delo instituted the first formal reserve program for scientists and engineers. A successful and productive program, it was soon extended to cover other branches of the Armed Forces. In 1951 he served as a special consultant to the Research and Development Command of the U. S. Airforce, concentrating on the efficient utilization of scientific manpower.

Completing his undergraduate work at Miami (Ohio) University in 1926, he was elected to membership in Phi Beta Kappa. In 1928, Dr. Delo was awarded the master of arts degree from the University of Kansas and in 1935, while studying under an Austin Fellowship at Harvard University, he received the doctor of philosophy degree.

Dr. Delo began his college teaching career as an instructor in Washington University, St. Louis, Mo., in 1929, moving to Northwestern University in 1930 to serve in the same capacity. In 1934, he became chairman of the Department of Geology at Lawrence College, Appleton, Wisconsin. Three years later, he was appointed chairman of the Department of Geology and Geography at Knox College, Galesburg, Illinois, a post he held until 1946.

While at Knox, Dr. Delo was certificated instructor in the civilian pilot training program (1939–43). From 1944 to 1946, while on a leave of absence from Knox, he served as a technical aide in the Office of Scientific Research and Development, Washington, D. C. He was awarded the Certificate of Merit by the Department of the Army in 1946 for his work with that office.

A contributor of numerous articles to technical and educational journals, Dr. Delo is also the co-author of *Years of This Land* (1943) and *Scientists in Uniform* (1948). The latter work is the only comprehensive report on the employment and utilization of our scientists and engineers by the Armed Forces during World War II.

Dr. Delo is a fellow of the Geological Society of America and a member of Beta Theta Pi, Sigma Xi, and the Staten Island Kiwanis Club. He has also been a trustee of the United Cerebral Palsy Association.

Dr. E. A. Eckhardt, of Gulf Research & Development Co., Honorary Member of the Society of Exploration Geophysicists, was present at the Inauguration as official representative of this society.

EXECUTIVE DIRECTOR, A.G.I.

It is announced that Dr. Robert W. Webb has accepted the joint position of Executive Director

of the American Geological Institute and Executive Secretary of the Division of Geology and Geography of the National Research Council, effective January 1, 1953.

Dr. Webb will be on leave of absence from his position as Professor of Geology, Department of Physical Science, Santa Barbara College, University of California.

FOREIGN EXCHANGE OF REPRINTS OF GEOPHYSICAL PAPERS

Listed below are the names and addresses of geophysicists who have expressed the desire to cooperate in the exchange of reprints between authors of geophysical papers in America and abroad.

DR. HANS V. HELMS, Geophysicist, Hannover, Germany, Goldener Winkel 4I.

PROF. CARLO MORELLI, Osservatorio Geofisico, Trieste II, Italy.

DR. A. SCHLEUSENER, Geophysicist, Hannover, Germany, Ludwig-Bruns-Strasse 17.

Each issue of *Geophysics* will contain a list of authors who wish to exchange reprints of their papers with those in other countries. All authors desiring to place their names and addresses on this list are requested to notify the business manager of the society.

M.I.T. DEPARTMENT OF GEOLOGY RENAMED

The Department of Geology at the Massachusetts Institute of Technology has been renamed the Department of Geology and Geophysics to recognize increased emphasis on instruction and research in geophysics within the Department.

The Department now offers two separate courses, one leading to the degree of bachelor of science in geology and the other to the degree of bachelor of science in geophysics. Either course satisfies the requirements for admission to the M.I.T. Graduate School for work toward advanced degrees in geology, geophysics, and geochemistry.

Although the two courses of study are essentially similar for the first two undergraduate years, they differ greatly in the third and fourth years. In these years, majors in geology follow the traditional advanced work in this area, while majors in geophysics take additional courses in mathematics, physics, and electrical engineering.

Both courses require the summer following the sophomore year to be spent at the M.I.T.–Nova Scotia Centre for Geological Sciences at Antigonish, Nova Scotia, where students learn surveying, mapping, and geological field methods.

An optional cooperative program in geophysical field training has also been arranged for the summer following the junior year with the Geophysical Service, Inc., of Dallas, Texas. The student participating in this program joins a field party engaged in seismic work in an area of active petroleum exploration.

SOCONY–VACUUM FELLOWSHIP IN PETROLEUM EXPLORATION SCIENCES

Provost Paul H. Buck announces establishment at Harvard University of the Socony-Vacuum Fellowship in Petroleum Exploration Sciences. The Fellowship is made possible by a grant from the Socony-Vacuum Oil Co., Inc., given "in recognition of the important and vital role played by American universities and colleges in training scientists and engineers."

Under the terms of the grant, the Fellowship is to be awarded to a graduate student in the field of the petroleum exploration sciences, preferably a student whose major interest is Petroleum Geology.

The recipient of the Fellowship for the present academic year is John M. Zeigler of Fort Pierce, Florida. Mr. Zeigler received his A.B. degree from the University of Colorado in 1947. He interrupted his graduate studies to go to Afghanistan as a member of a geological expedition. Following two years of professional work as a petroleum geologist, he entered the Harvard Graduate School in 1951.

In offering the Fellowship to Harvard, Mr. J. I. Laudermilk of the Socony-Vacuum Oil Co. wrote, "We realize that the petroleum industry was founded on the vision and knowledge of educated people and that its continued prosperity is dependent upon the constant supply of scientific trained personnel as well as scientific ideas."

PERSONAL ITEMS

S. PRESTON WEATHERBY has moved from the Latin-American Exploration Company, No. 117, 101 y 102, Mexico 1 D.F. to the Western Geophysical Company, 523 West Sixth Street, Los Angeles 14, California.

H. B. PEACOCK has sold his interests in Geophysical Service Inc. and affiliated companies to his associates and has resigned his position on the Board of Directors. He will continue his professional duties until the end of 1952, after which he expects to enter the geophysical consulting field.

Dr. Peacock entered the field of exploration geophysics with Geophysical Research Corporation in 1926 and has been associated with GSI since its organization in 1930. He is a Past President of the Society of Exploration Geophysicists and has been active in the society for many years.

A. P. CRARY, of the Air Force Cambridge Research Center, returned in late October, 1952, from T-3, Fletcher's Ice Island in the Arctic, where he had spent over 200 days within 150 miles of the Pole. Research conducted there included seismic, gravitational, oceanographic, and meteorological work.

D. M. STEEL has been elected to the position of vice-president of Geotechnical Corporation of Delaware with headquarters in Dallas, Texas. Mr. Steel is a graduate of Hendricks College, Arkansas. He joined Geotechnical in 1938, was promoted to party chief in 1943, and supervisor in 1947. He resides at 251 Avenue F, Billings, Montana, and will be in charge of Geotechnical's operations in the Rocky Mountain and Williston Basin areas.

GERALD H. WESTBY, president of Seismograph Service Corporation, has accepted chairmanship of the scientific and technical committee for the May 14–23, 1953 International Petroleum Exposition, according to W. G. Skelly, exposition president, Tulsa, Oklahoma.

Mr. Westby's committee will be responsible for the selection of exhibits and displays to best describe the development of oil progress from the time of Col. Edwin L. Drake to the present. Special emphasis will be given to exhibits exemplifying and explaining the technological developments of the last five years since the 1948 exposition.

HOWARD E. ITTEN, formerly division geophysical supervisor for Stanolind Oil & Gas Co., Fort Worth, Texas, announces the formation of Empire Geophysical, Inc., of which he is president, at 3615 West Sixth Street, Fort Worth.

ROBERT M. DREYER has been granted a leave of absence from his duties as Professor of Geology and Geophysics at the University of Kansas to accept a position as geologist in charge of the uranium division of Kerr-McGee Oil Industries. Professor R. C. Moore will assume the departmental chairmanship.

JAMES K. ZIEGLER has been elected vice president in charge of Century Geophysical Corporation of Canada, a wholly-owned subsidiary of Century Geophysical Corp., Tulsa, Oklahoma. Mr. Ziegler was formerly manager in charge of Canadian operations for Century, and his address remains 233 Examiner Bldg., Calgary, Alta., Canada.

LEMAN MILTON HOLLEY and JENNINGS G. SMITH are recipients of one year associate memberships in the S.E.G. (transfer from student) presented by the Geophysical Society of Tulsa in June of this year. The action came in recognition of scholastic achievement. The men were the two top members of the class in geophysics graduating from The University of Tulsa in June.

Holley has joined Schlumberger Well Surveying Corp., as engineering trainee and Smith has joined Western Geophysical Company as a party chief.

COLONEL MERLE C. BOWSKY has been appointed Chief of Staff at U. S. Army SW Signal Corps Training Center, Camp San Luis Obispo, California.

D. H. SCOTT has been appointed head of the gravity staff in the Houston geophysical office of The Texas Company, transferring from the Pacific Coast division where he was supervisor of geophysical operations. Mr. Scott will be succeeded by T. H. Braun, of The Superior Oil Co., as Vice President, Southern District, of the Society of Exploration Geophysicists, Pacific Coast Section.

GERALD H. WESTBY, president of Seismograph Service Corp., Tulsa, was guest of honor at the London Meeting of the European Association of Exploration Geophysicists held at Manson House last May 22 and 23.

ADDITIONAL APPLICATIONS APPROVED FOR PUBLICATION

Listed below are candidates whose applications were approved by the Executive Committee too late for inclusion in the customary list which appears elsewhere in this issue.

ACTIVE

Tom Prickett, Jr. (J. P. Woods, O. C. Clifford, C. H. Hightower)

TRANSFER TO ACTIVE MEMBERSHIP

William Allen, Jr. (E. E. Maillot, H. E. Stommel, W. E. Heinrichs, Jr.)
Harold Truett Austin (L. K. Mower, F. Goldstone, O. B. Manes)
Charlie B. Autrey (B. D. Farrow, J. E. Jett, W. B. Heroy, Sr.)
Malcolm Evan Baker (T. R. Shugart, H. M. Houghton, Hal R. Adams)
William Edwin Bannister (F. A. Hale, C. M. Moore, Jr., R. E. Doe)
Edward Irving Barton (W. B. Robinson, Mark D. Butler, W. C. Lamb)
Carl Dalquest Bearden (C. C. Ludwick, J. E. Walker, R. C. Kendall)
Owen Burtis Bennett (Andrew Gilmour, A. I. Innes, K. M. Lawrence)
Wesley Edward Bird, Jr. (H. R. Prescott, B. G. Swan, L. E. Whitehead)
Henry Francis Birkenhauer, S.J. (J. B. Macelwane, S.J., L. Don Leet, V. J. Blum, S.J.)
Ross Edwin Brannian (C. H. Green, C. M. Moore, Jr., T. A. Halbrook)
Gordon Dwain Cloepfil (C. H. Green, H. B. Peacock, F. J. Agnich)
Kenneth Stanley Cressman (L. Y. Faust, F. F. Campbell, Andrew Gilmour)
Dean Lewis Cummins (Booth Strange, Walter Baird, J. A. Harris)
Clem Alfred Dahse (W. A. Mathews, H. E. Itten, K. C. Thompson)
Robert Eldon Doe (Francis A. Hale, Phil P. Gaby, C. M. Moore, Jr.)
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ERRATA

Mr. J. E. White, Magnolia Petroleum Co., Dallas Texas, has kindly called my attention to an error in my paper "Elastic Waves Through a Packing of Spheres" issued in *Geophysics*, Vol. 16, pp. 673–685. The following corrections should be made:

(9) for $(1-\hat{\nu})^2$ read $(1-\hat{\nu}^2)$

(10) read: $2\sqrt[3]{\dfrac{9(1-\hat{\nu}^2)^2P^2}{16\hat{E}^2R}}$ = relative displacement of the centers of the spheres.

(14) and (19) for $\hat{c}=$ read $2\hat{c}=$

(31) for $L=$ read $\sqrt{2}\cdot L=$

Fig. 4 dry: the numercal values for v_1 are to be divided by $\sqrt{2}$.

wet: depth:	0 m	100 m	200 m
read: v_1 vertical:	1742	1887	1923 m/sec
v_1 horizontal:	1742	1746	1747 m/sec

Fig. 6: The numerical values for τ are to be multiplied by $\sqrt{2}$.

The numerical values for $\dfrac{da}{d\tau}$ are to be divided by $\sqrt{2}$.

F. GASSMANN

In the article by James R. Wait in the October 1952 issue of *Geophysics*, Vol. 17, No. 4, p. 978 the denominators in the expressions for the ϕ components of the fields should be $4\pi r^2$.

STATEMENT OF THE OWNERSHIP, MANAGEMENT, CIRCULATION, ETC., REQUIRED BY THE ACTS OF CONGRESS OF AUGUST 24, 1912, AND MARCH 3, 1933 of GEOPHYSICS, published quarterly at Menasha, Wisconsin for January, 1953.

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County of Tulsa }

Before me, a Notary Public in and for the State and county aforesaid, personally appeared Colin C. Campbell, who, having been duly sworn according to law, deposes and says that he is the business manager of GEOPHYSICS, and that the following is, to the best of his knowledge and belief, a true statement of the ownership, management (and if a daily paper, the circulation, etc., of the aforesaid publication for the date shown in the above caption, required by the Act of August 24, 1912, as amended by the Act of March 3, 1933, embodied in section 537, Postal Laws and Regulations, printed on the reverse of this form, to wit:

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Sworn to and subscribed before me this 10th day of September, 1952.
[SEAL]

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(My commission expires October 16, 1952.)

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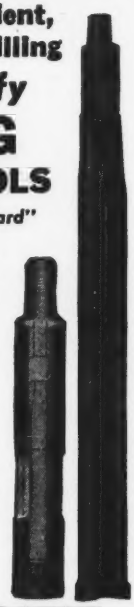

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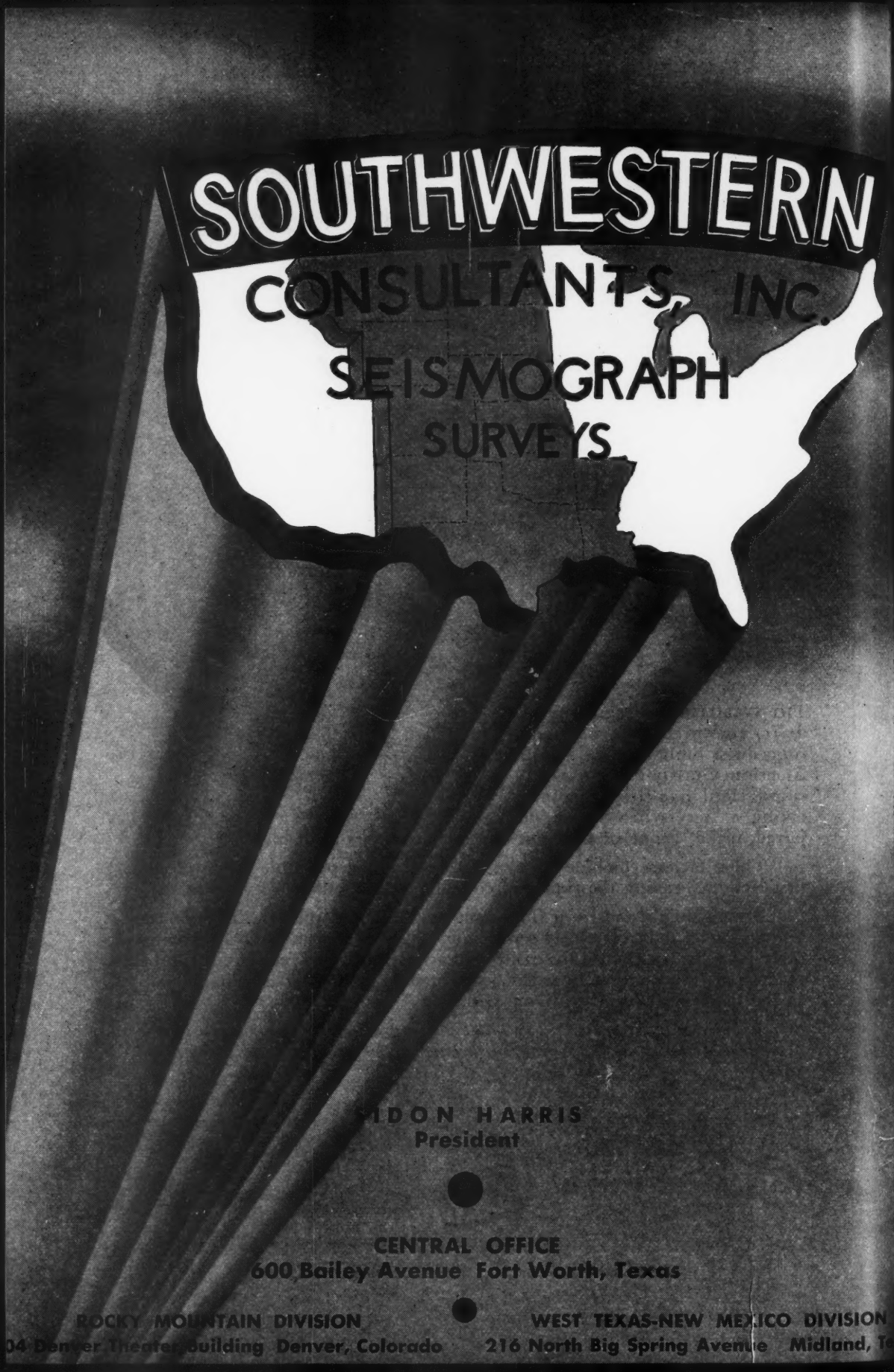
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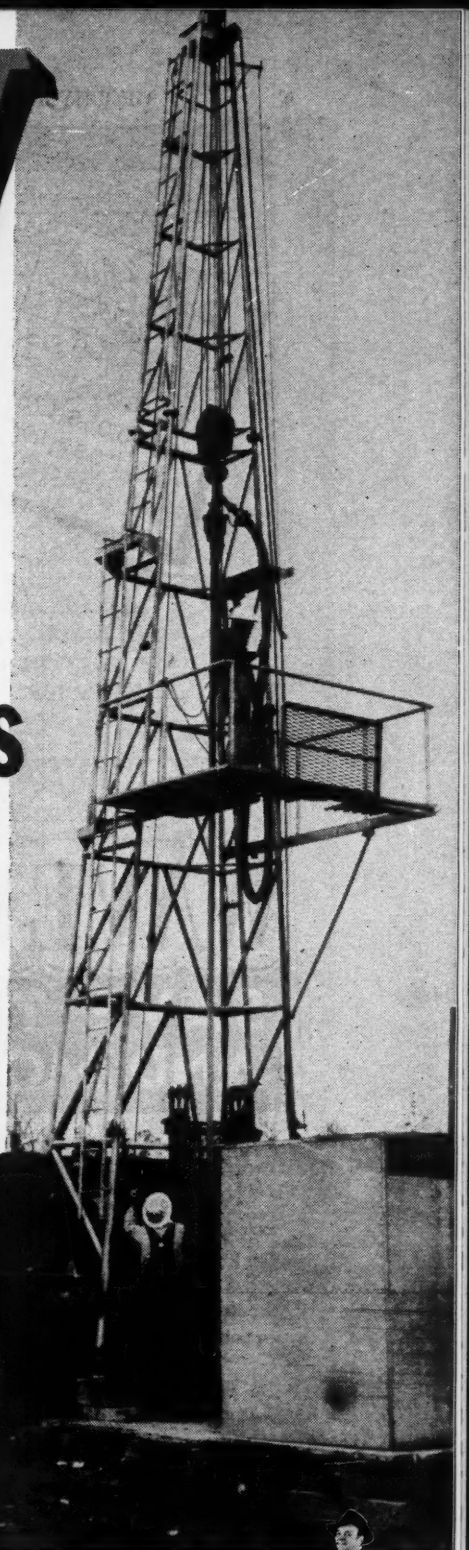

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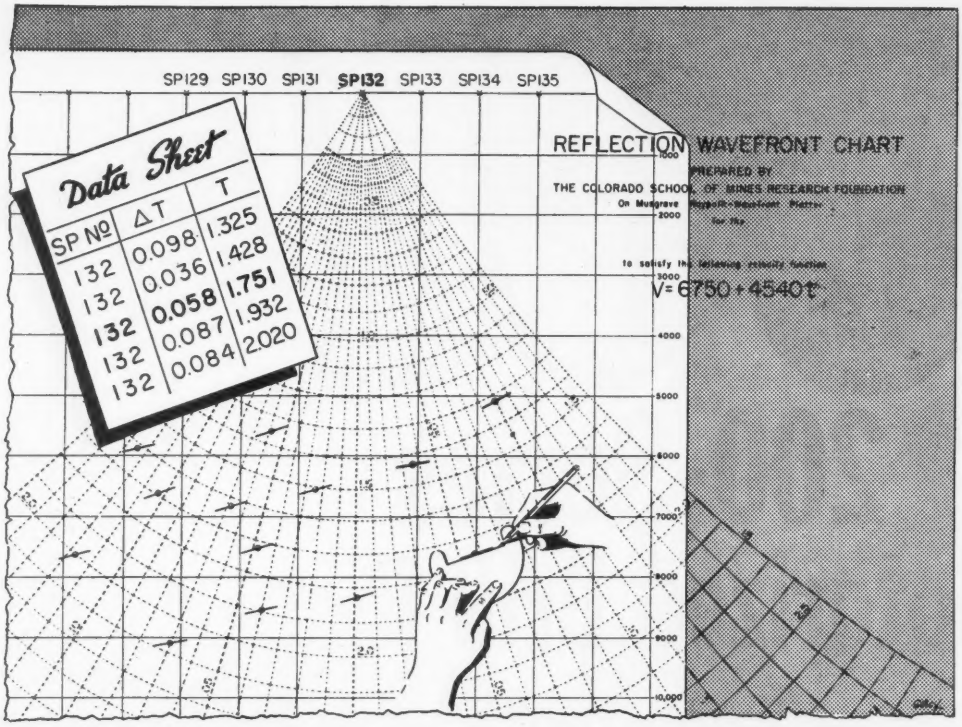
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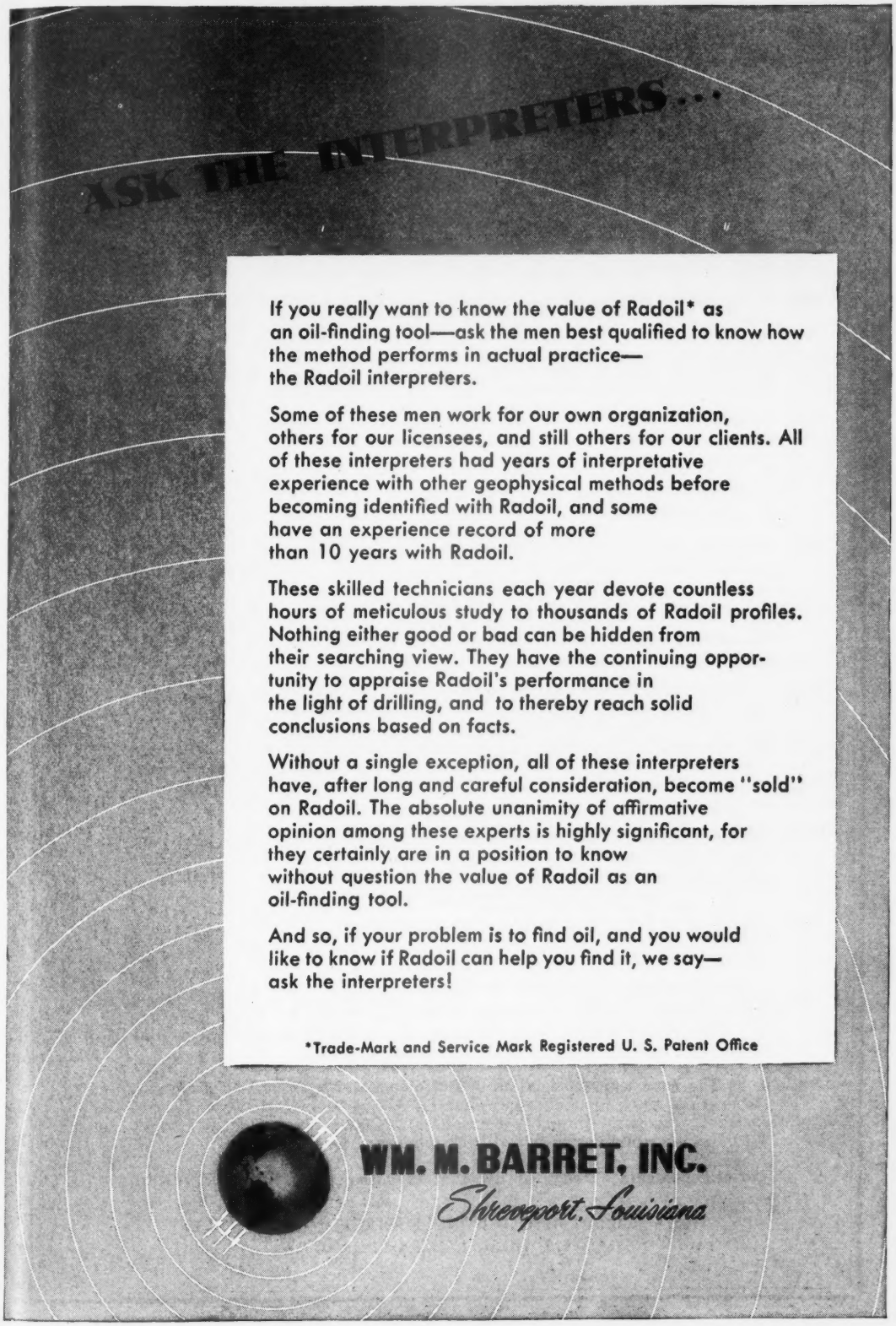
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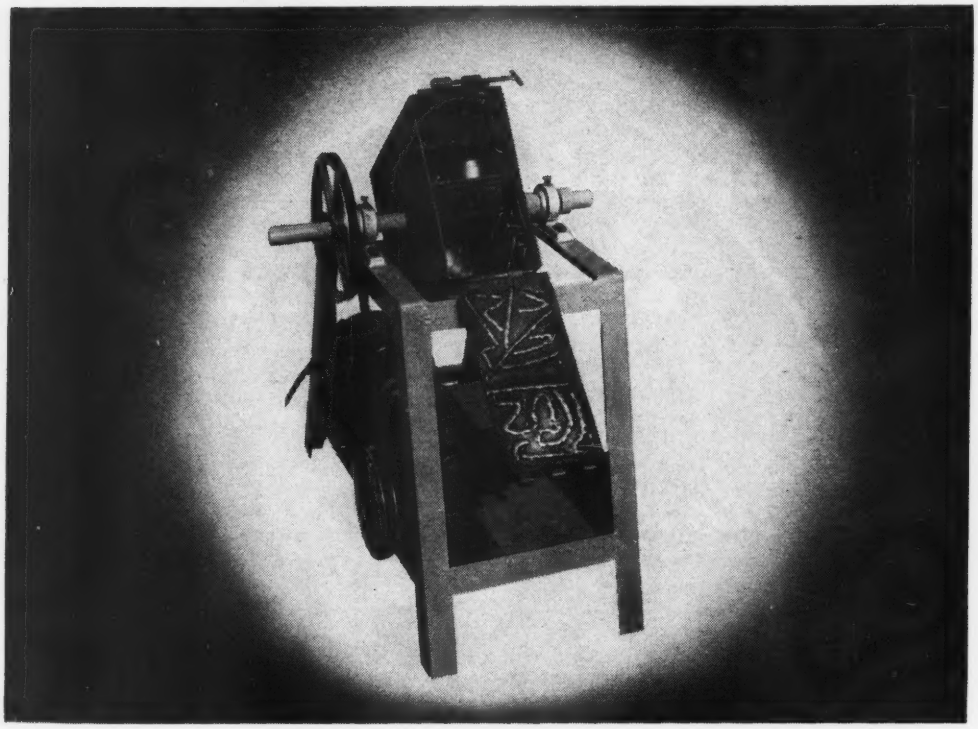

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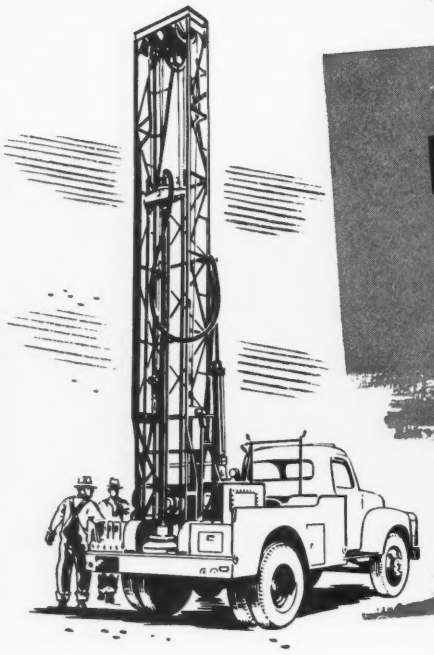

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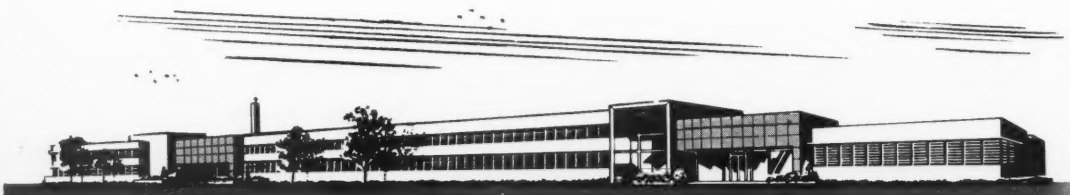

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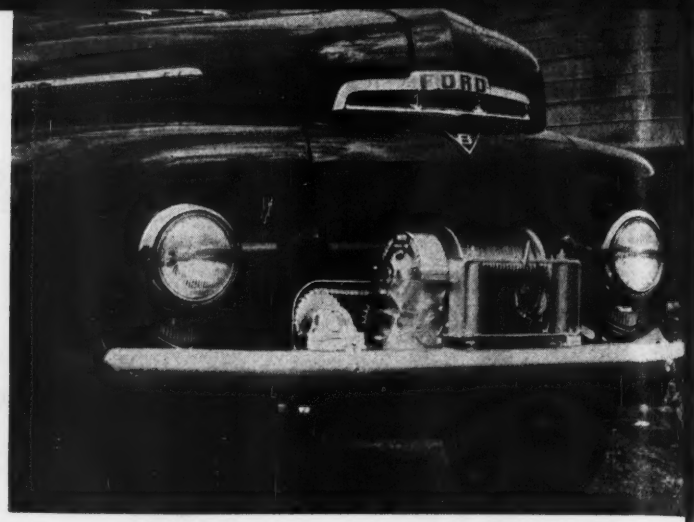

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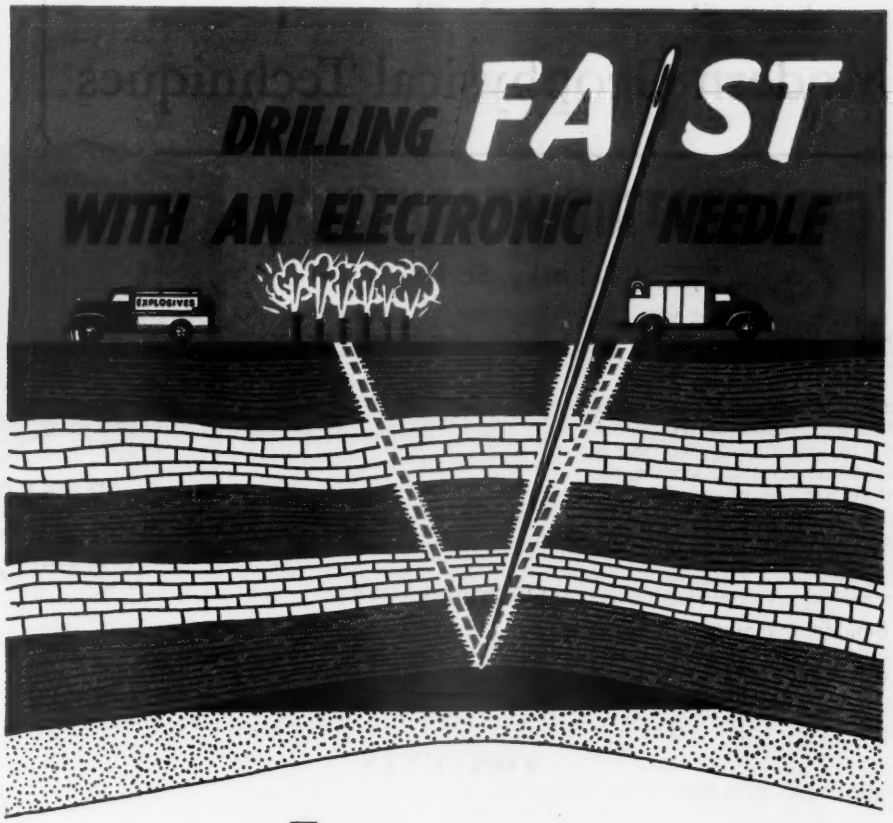

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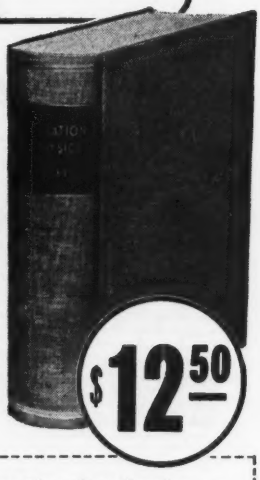

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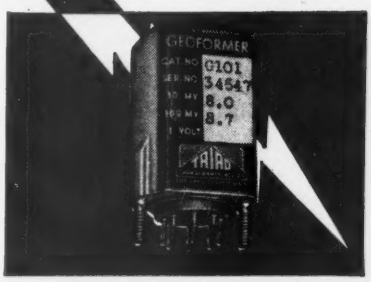

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Type No.	Primary Impedance in Ohms	Secondary Impedance in Ohms	Primary Inductance @ 10 MV	Primary Inductance @ 100 MV	DC Resistance Pri. in Ohms	DC Resistance Sec. in Ohms	Stray Fields Shield	Turn Ratio	Case	Weight
G-101	500**-333-233 200**-125*-67½** 50*-17*	145000 CT	8.3 h.	9.6 h.	100	10000	P1-H	1-17	GP-1	3.2 oz.
G-201	500** or 125*	145000 CT	8.3 h.	9.6 h.	100	10000	P1-H	1-17	GP-1	3.2 oz.
G-135	10000** or 2500*	75000** or 18750*	300 h.	325 h.	2500	8500	P1-H	1-2.75	GP-1	3.2 oz.
G-235	10000** or 2500*	75000** or 18750*	300 h.	325 h.	2500	8500	P1-H	1-2.75	GP-1	3.2 oz.

Type No.	Primary Impedance in Ohms	Secondary Impedance in Ohms	Primary Inductance @ 100 MV	Primary Inductance @ 1 Volt	DC Resistance Pri. in Ohms	DC Resistance Sec. in Ohms	Stray Fields Shield	Turn Ratio	Case	Weight
G-150	15000 CT	16**-12-8**-6½ 4*-2*-1½**-.35*	1000 h.	1200 h.	5000	4	P1-H	30.5-1	GP-1	3.2 oz.
G-155	15000 CT	60**-45-30**-24 15*-7½-5**1.3*	1000 h.	1200 h.	5000	18	P1-H	15.8-1	GP-1	3.2 oz.
G-250	15000 CT	16**-12-8**-6½ 4*-2*-1½**-.35*	1000 h.	1200 h.	5000	4	P1-H	30.5-1	GP-1	3.2 oz.
G-255	15000 CT	60**-45-30**-24 15*-7½-5** 1.3*	1000 h.	1200 h.	5000	18	P1-H	15.8-1	GP-1	3.2 oz.
G-175	15000 CT	240000 CT and 35	200 h.	240 h.	2000	9800 55	P1-H	1-4 20.6-1	GP-1	3.2 oz.
G-275	15000 CT	240000 CT and 35	200 h.	240 h.	2000	9800 55	P1-H	1-4 20.6-1	GP-1	3.2 oz.

Type No.	Inductance 100 MV	Inductance 1 Volt	$Q=\frac{WL}{R}$ @ 60 cy.	DC Resistance in Ohms	Low Percentage Taps	Stray Field Shield	Case	Weight
G-181	1050**-800** 550**-80**-260* 180*-120* 925-775-670-410 315-200	1135**-860** 594**-85**-280* 210*-140* 995-830-725-440 340-215	9	11500	None	P1-H	GP-1B	3.4 oz.
G-184	1000** h. 250* h.	1040** h. 260* h.	9	13000	4 - 2%	P1-H	GP-1B	3.4 oz.
G-185	500** h. 125* h.	550** h. 129* h.	9	10500	4 - 2½%	P1-H	GP-1B	3.4 oz.
G-281	(Inductances Same As G-181)		9	11500	None	P1-H	GP-1B	3.4 oz.
G-284	1000** or 250*	1040* h. or 260*	9	13000	4 - 2%	P1-H	GP-1B	3.4 oz.
G-285	500** or 125*	550** or 129*	9	10500	4 - 2½%	P1-H	GP-1B	3.4 oz.

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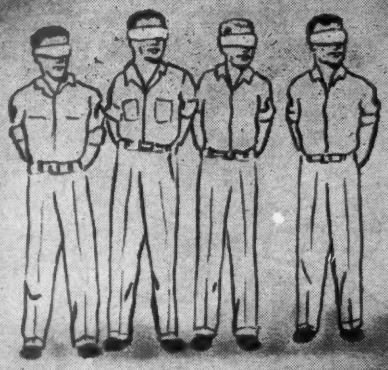

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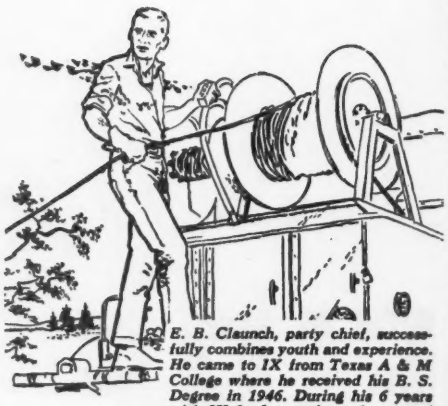

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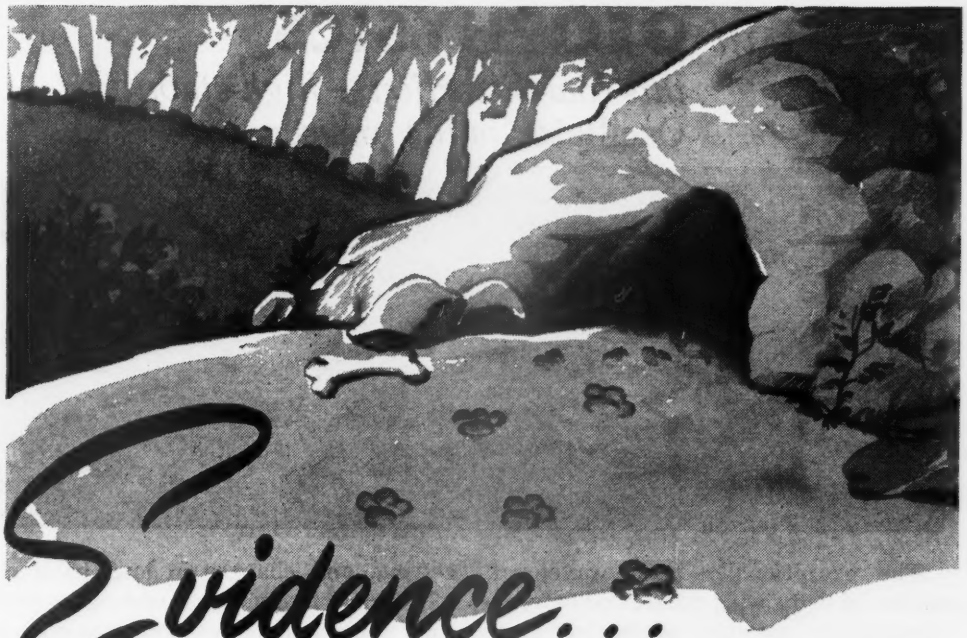

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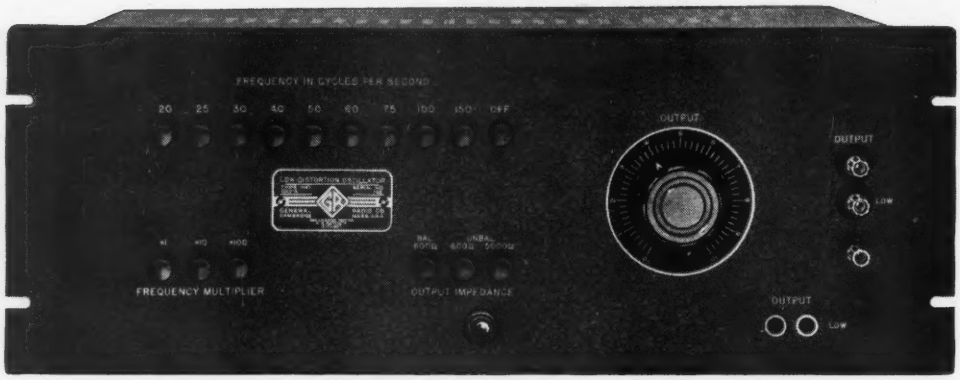

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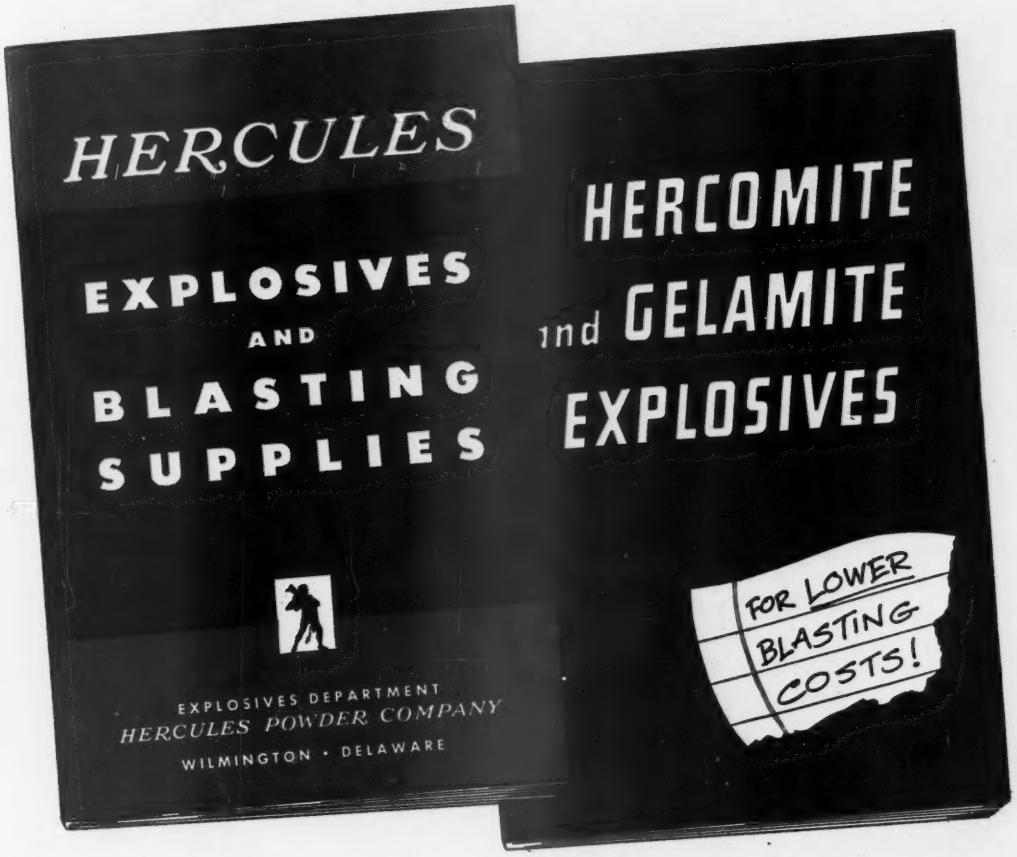

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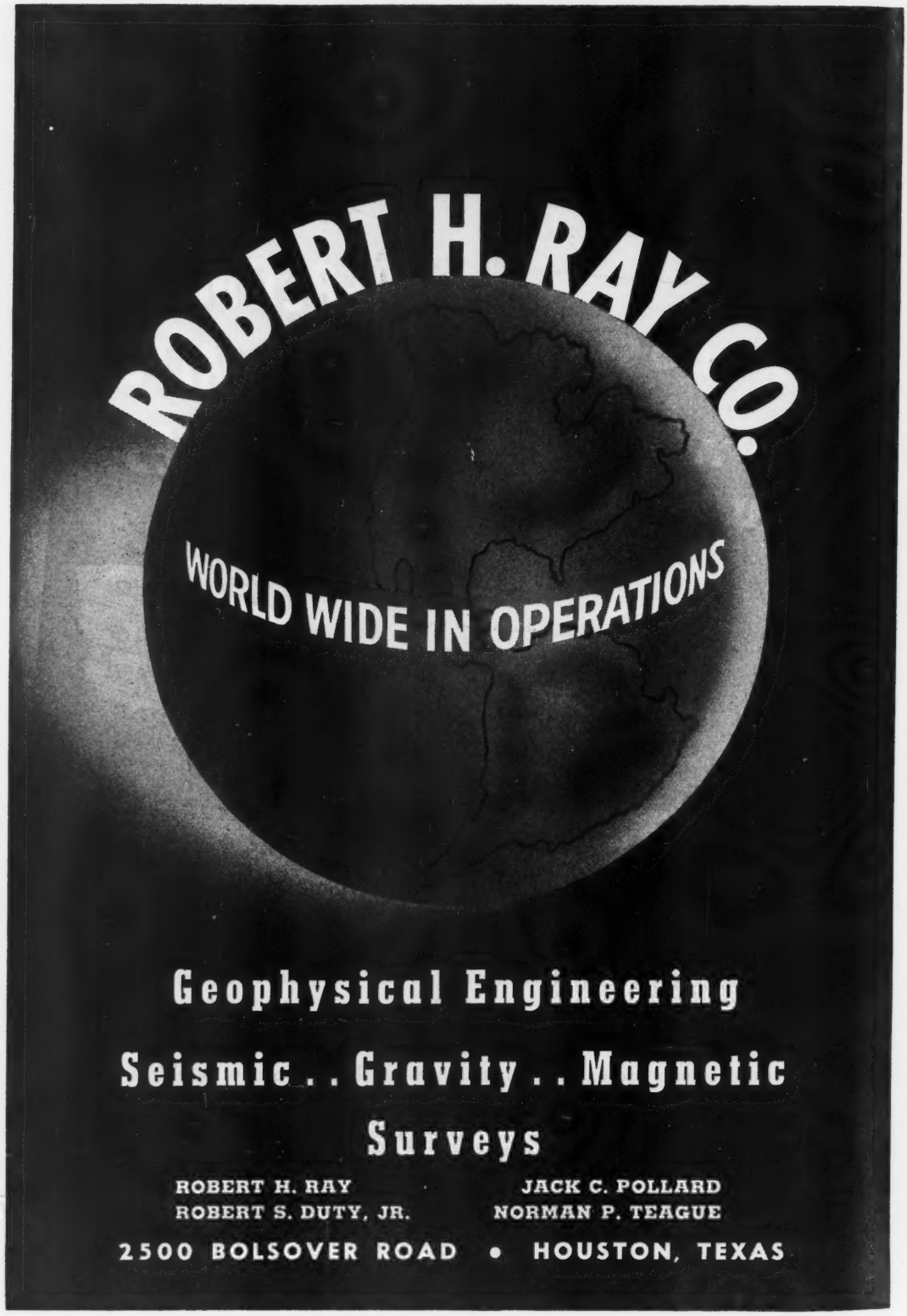
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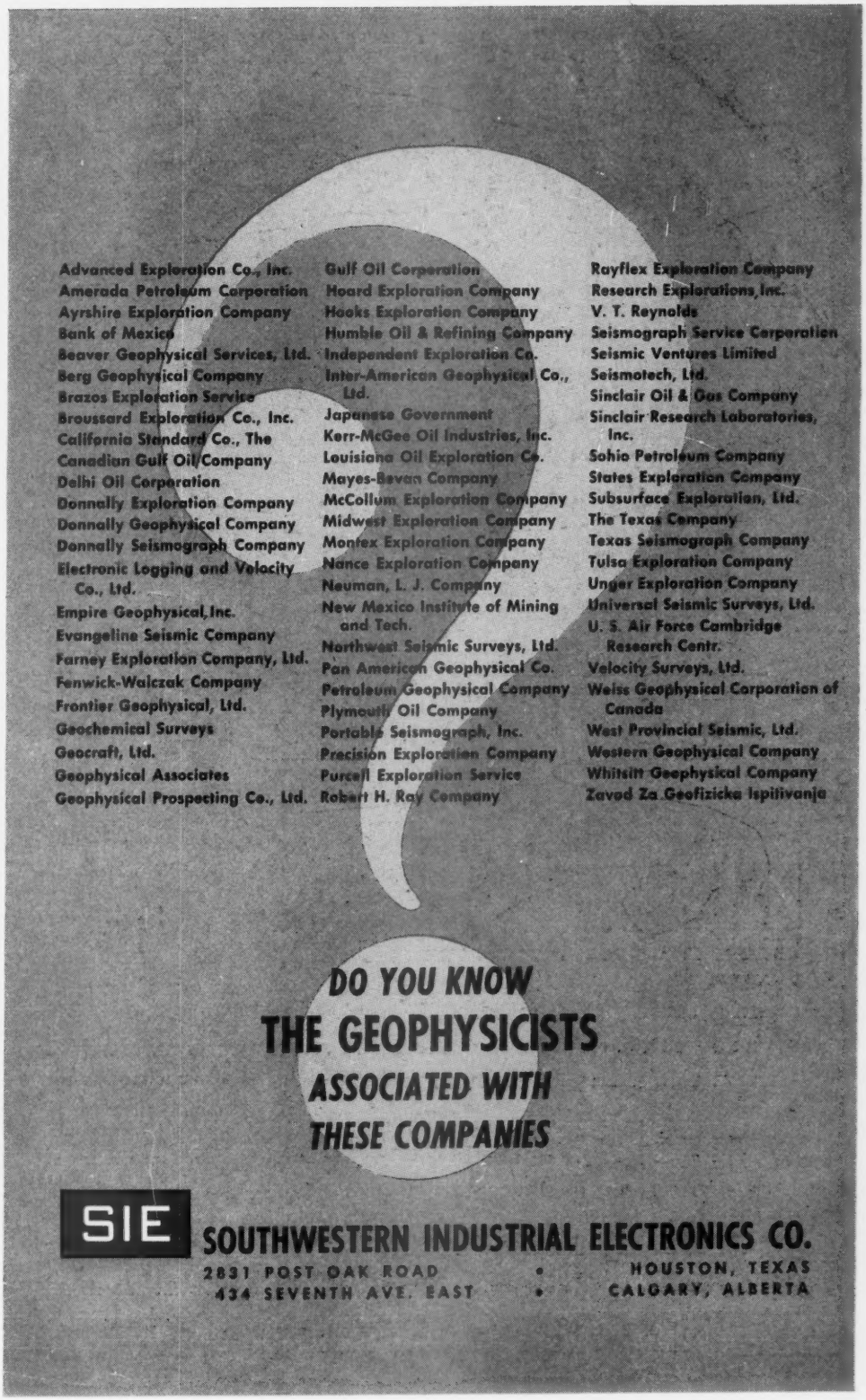
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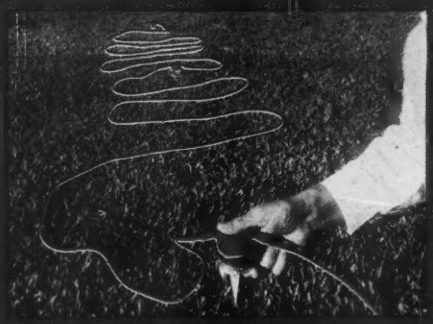

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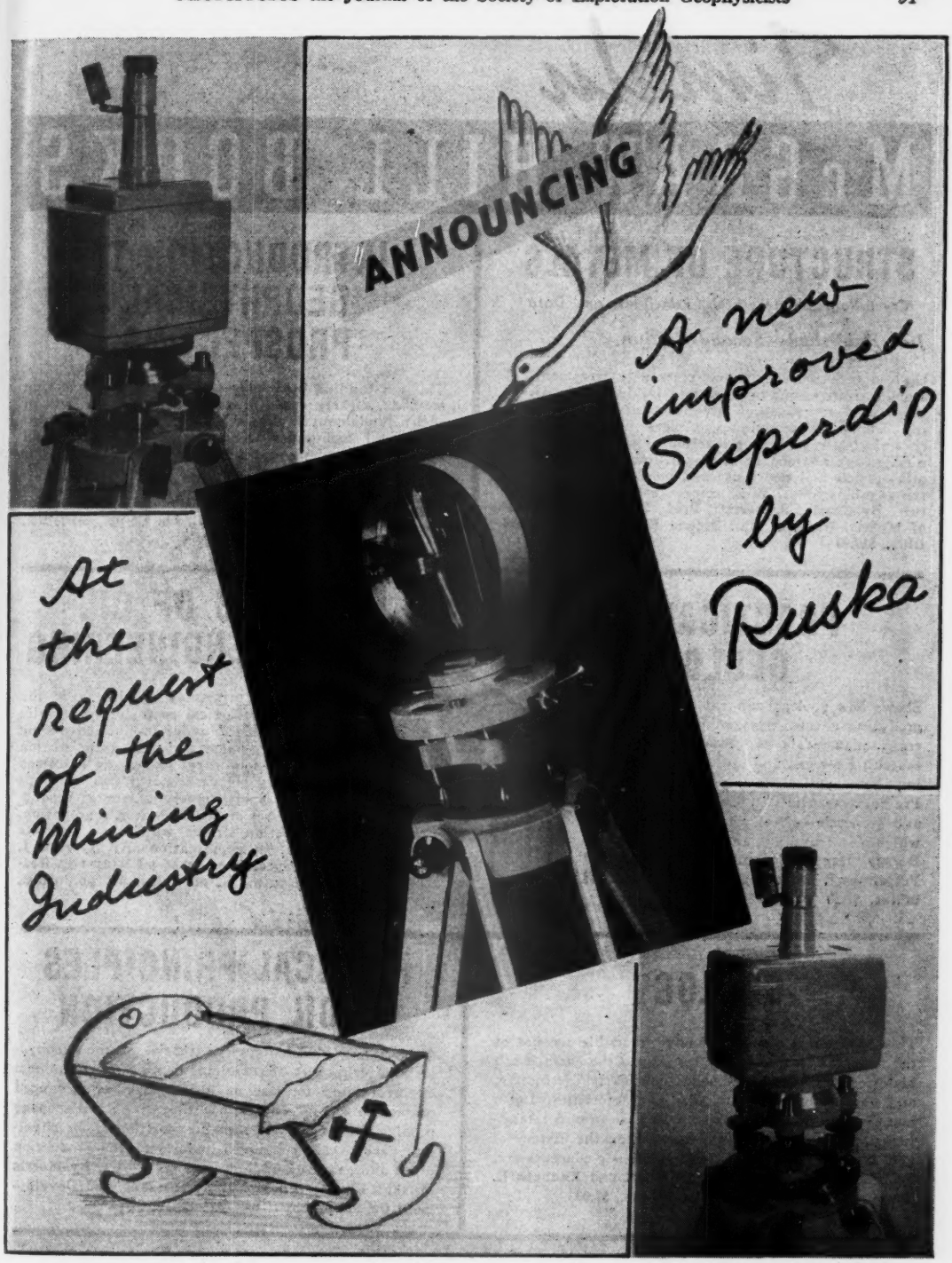

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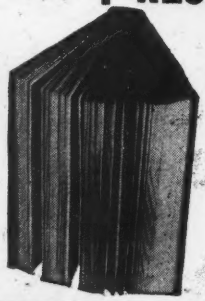

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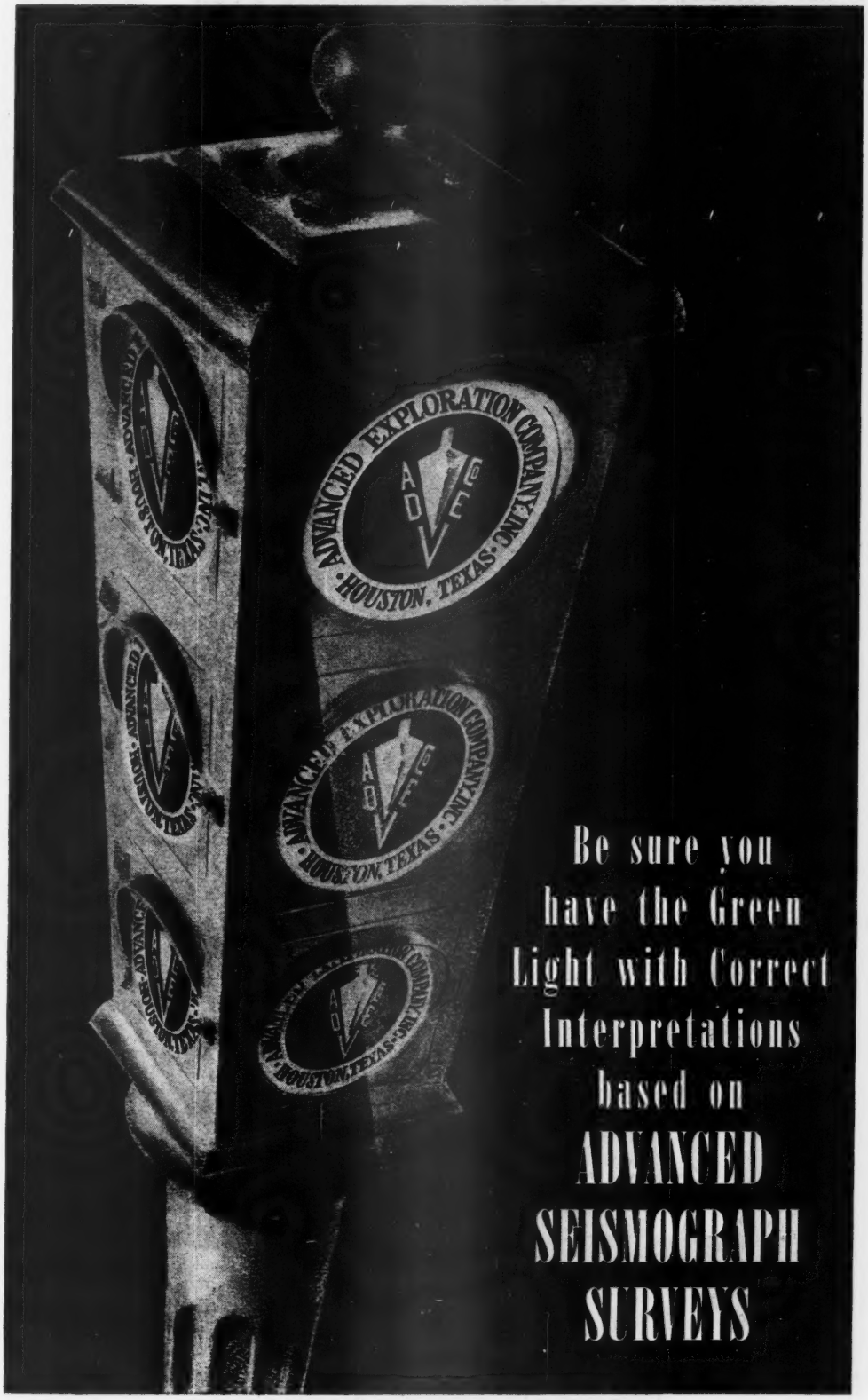
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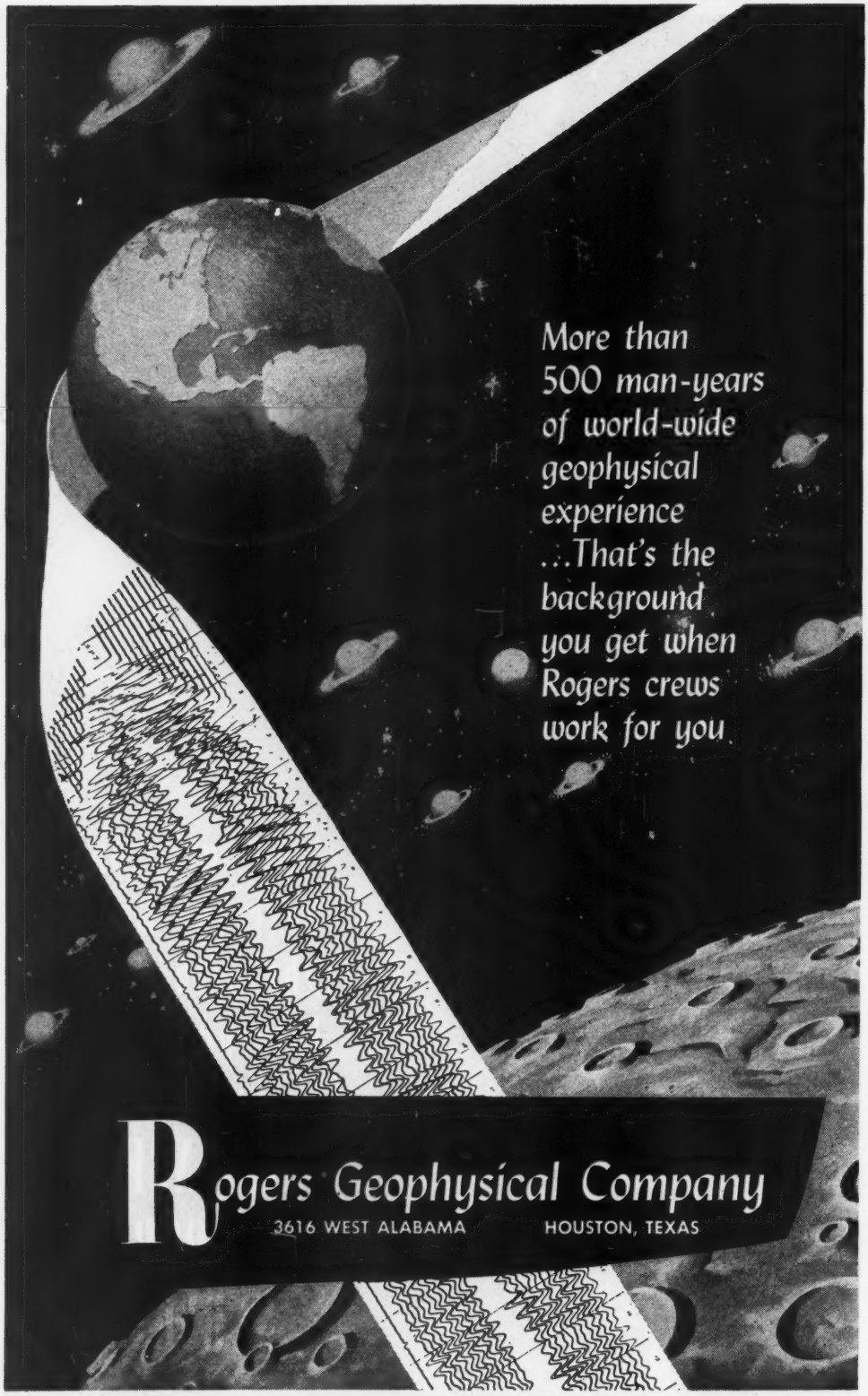
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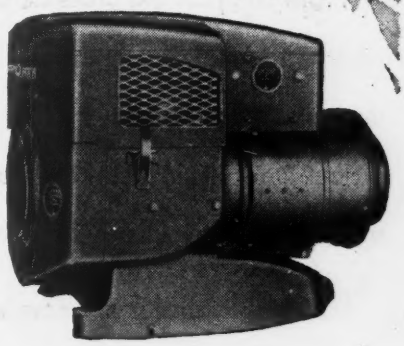

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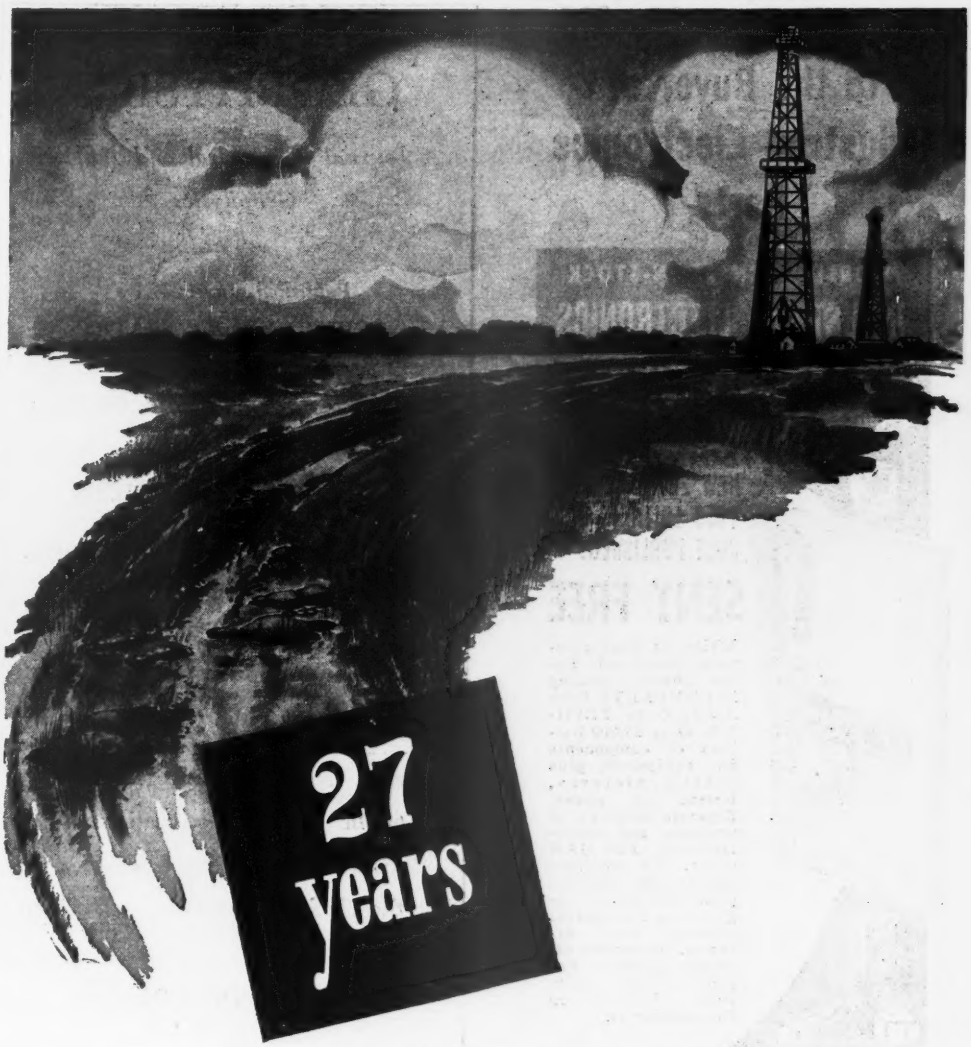

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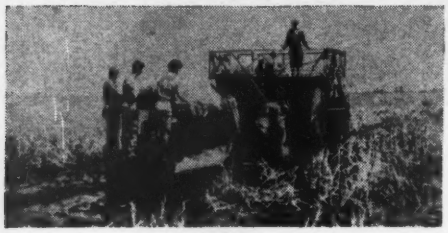

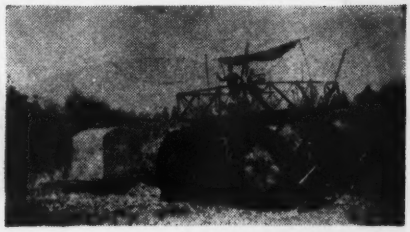

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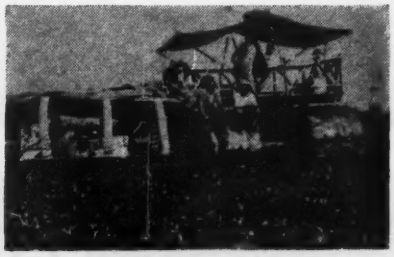

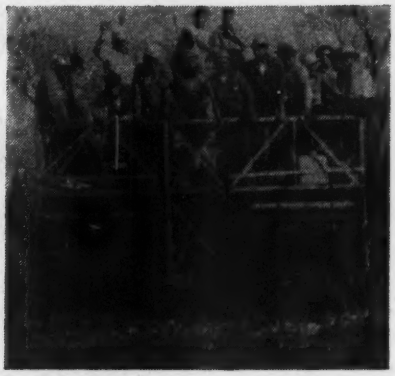

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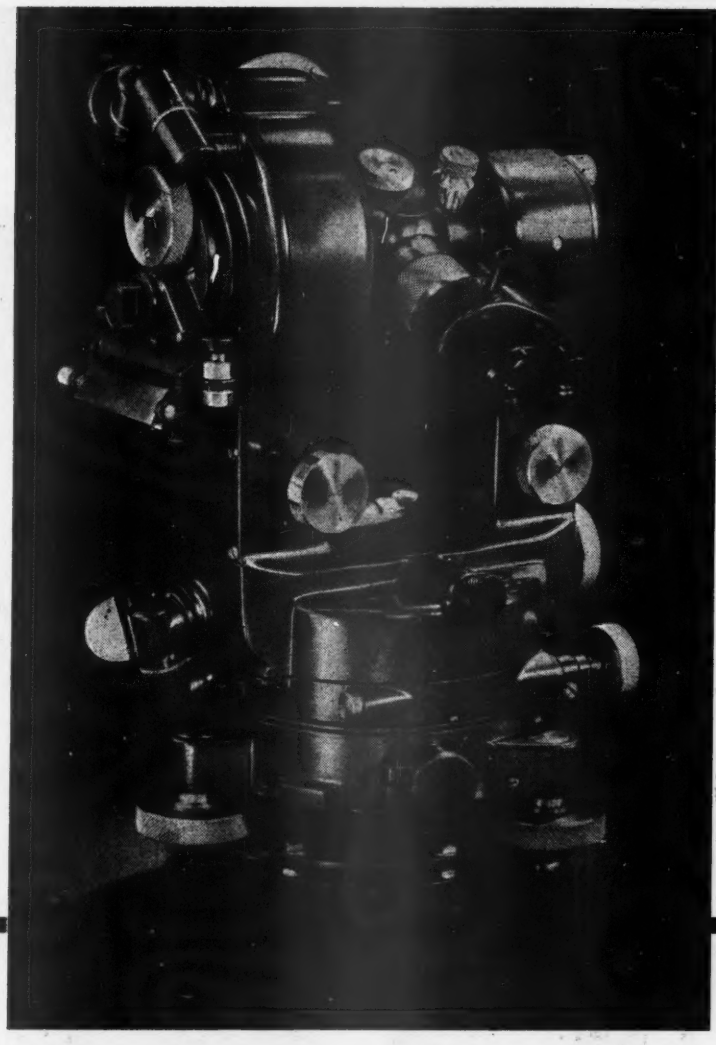

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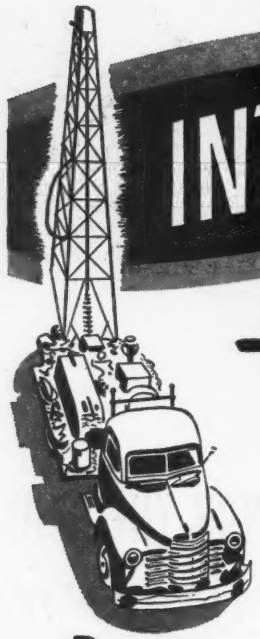

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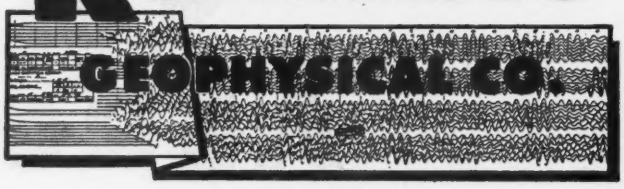

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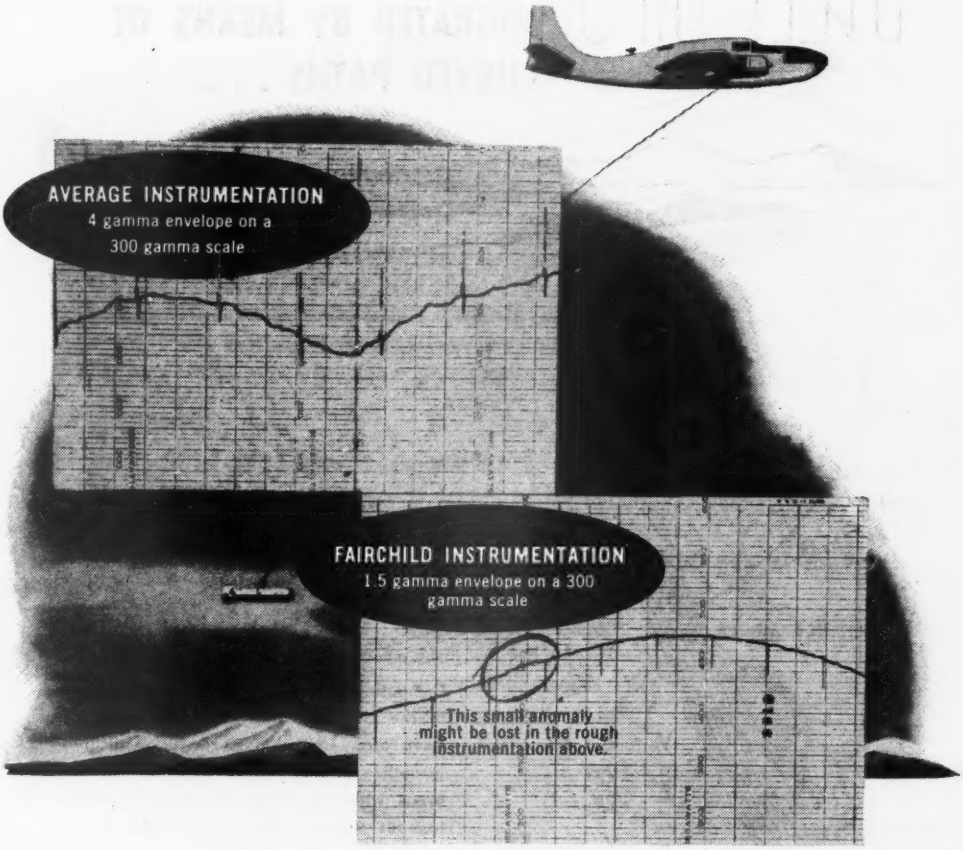

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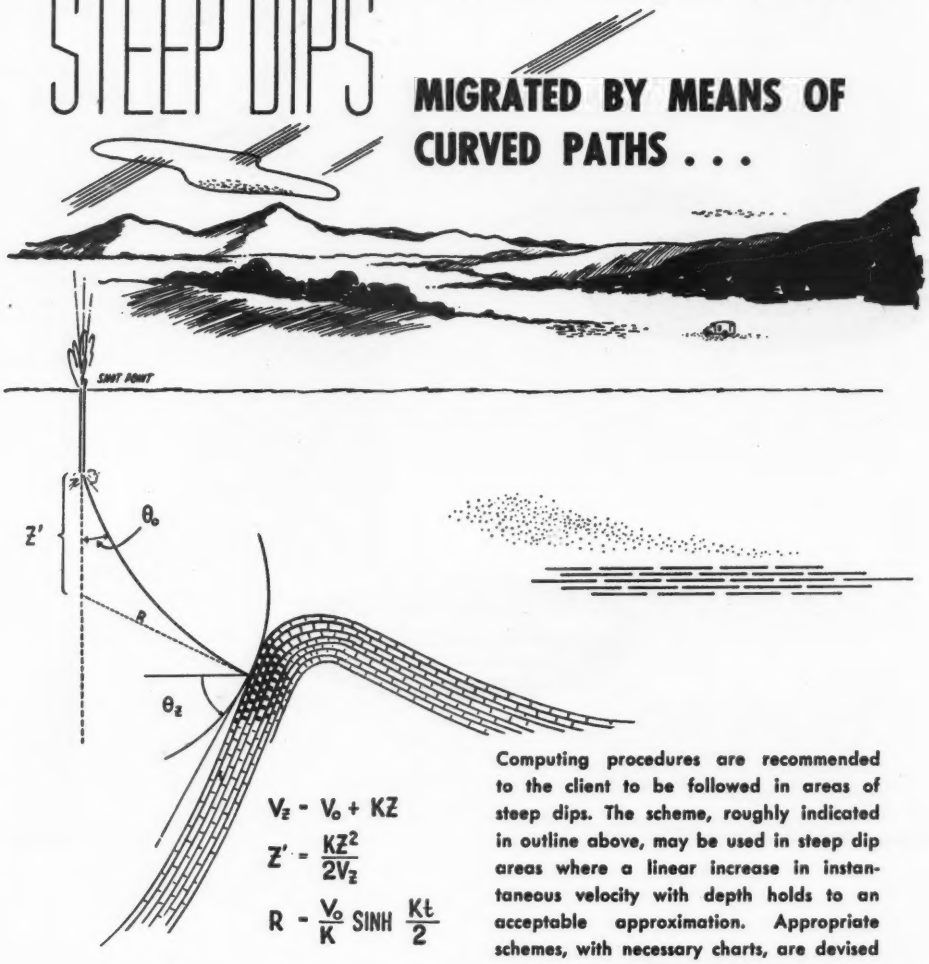

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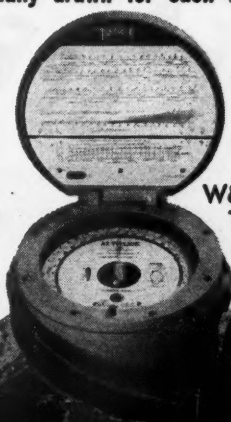

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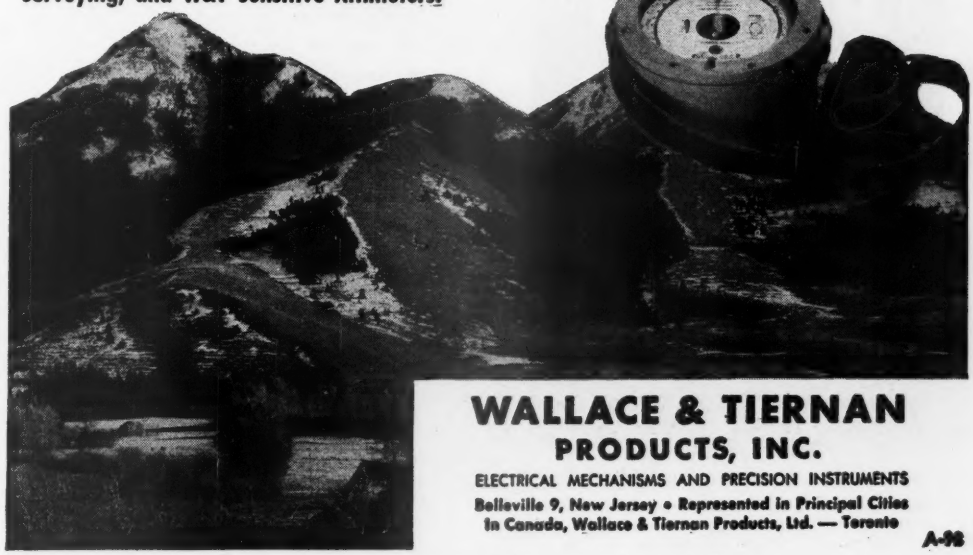

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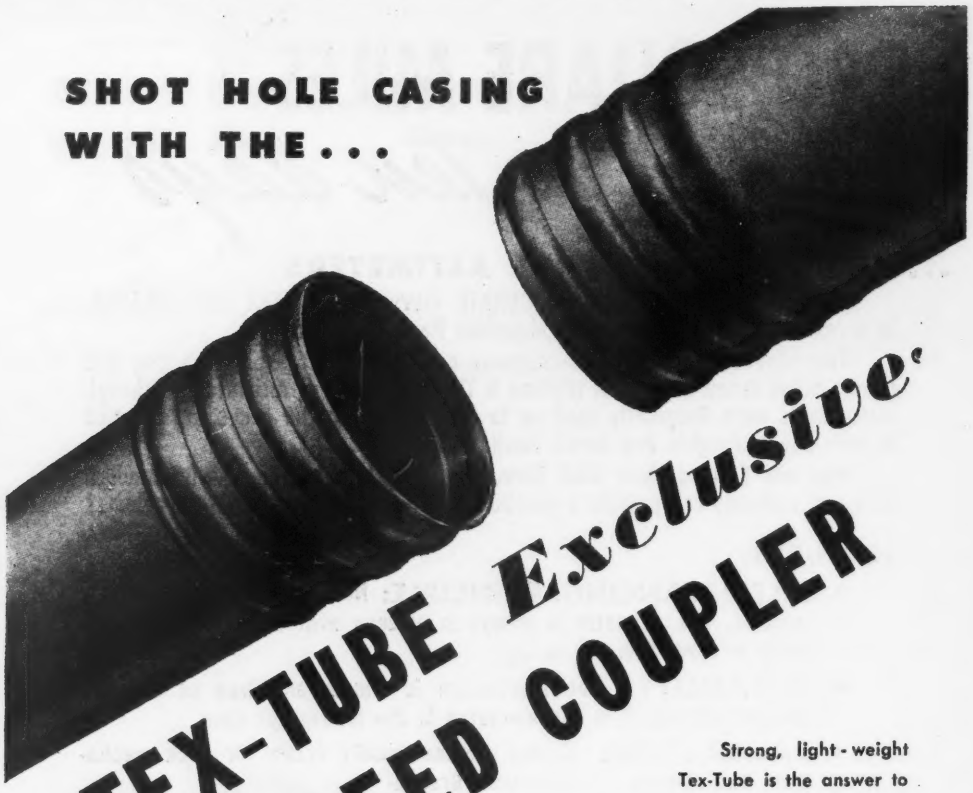

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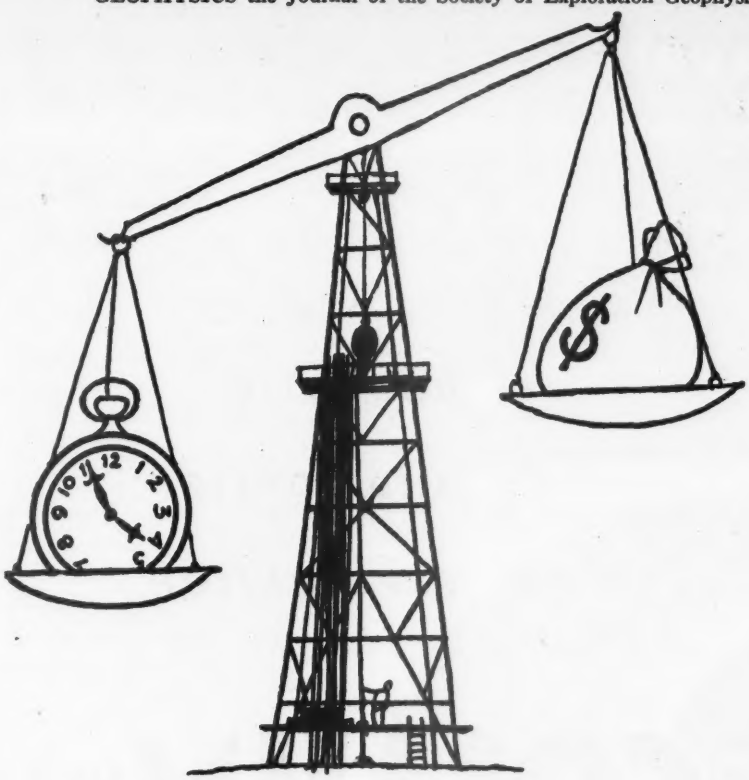

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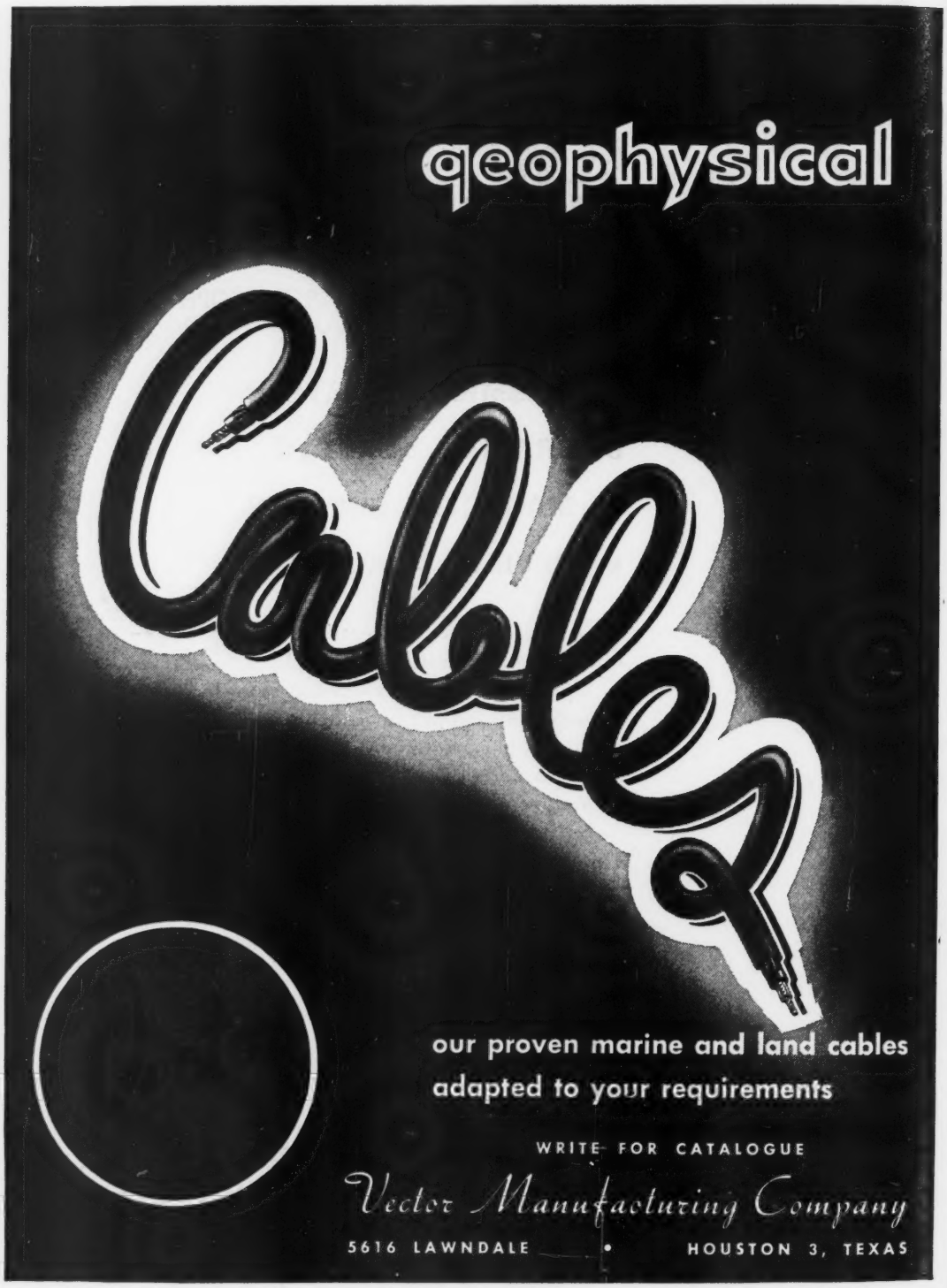
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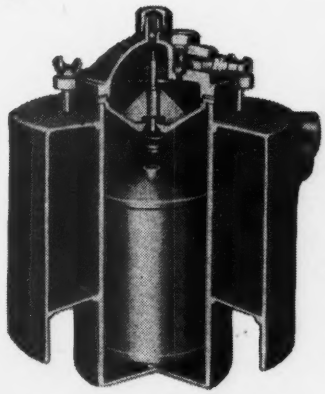

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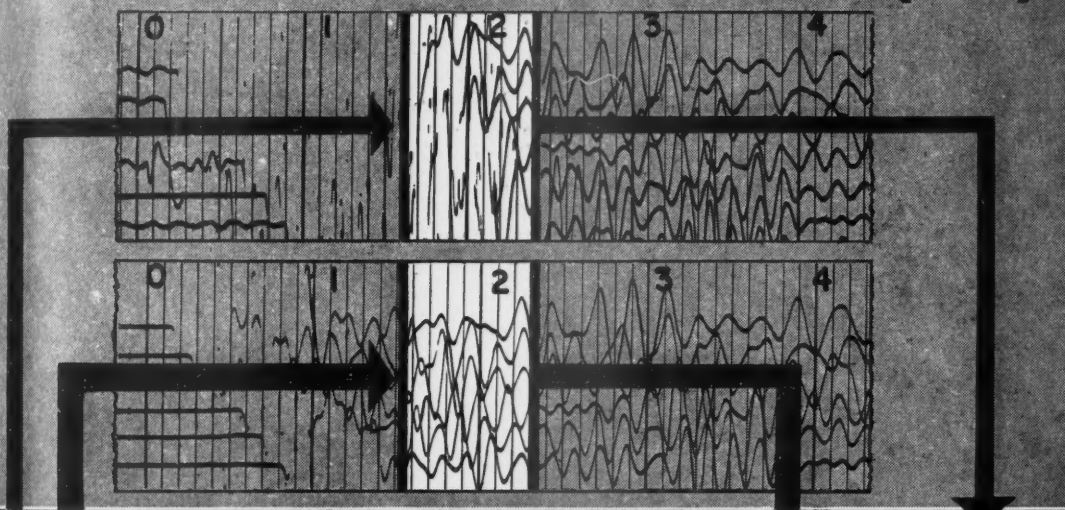

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